IPHC Management Strategy Evaluation (MSE): Update

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PURPOSE

To provide an update on the progress of the IPHC Management Strategy Evaluation process and seek recommendations for future work.

INTRODUCTION

At the 2017 Annual Meeting (AM093) Commissioners supported a revised harvest policy that separates the scale and distribution of fishing mortality (Figure 1) and accounts for fishing related mortality of Pacific halibut of all sizes and from all sources. Furthermore, the Commission identified an interim "hand-rail" or reference for harvest advice based on a *status quo* SPR (46%), which uses the average estimated coastwide SPR for the years 2014–2016 from the stock assessment. The justification for using an average SPR from recent years is that this corresponds to fishing intensities that have resulted in a stable or slightly increasing stock, indicating that, in the short-term, this may provide an appropriate fishing intensity that will result in a stable or increasing spawning biomass.

The 2016 stock assessment predicted a 68% chance that the spawning biomass will decline in 2017 and a 6% chance that it will decline more than 5% under the status quo SPR fishing intensity (Table 4 in Stewart and Hicks (2017)). The greater than 50% chance of decline, although a slight decline, is inconsistent with the justification behind the status quo SPR, indicating that the status quo SPR may not determine a fishing intensity that will meet the long-term conservation, yield, and stability goals and objectives defined by the MSAB. Therefore, an evaluation of fishing intensities, through simulation, should be done. A very brief description of the framework and components of these simulations is given below, followed by a summary of the results presented at MSAB10 in October 2017. Details of the framework presented at SRB11 (IPHC-2017-SRB11-09) and MSAB10 (IPHC-2017-MSAB10-09 Rev_1) are available on the IPHC website. First, though, draft goals, objectives, and performance metrics defined by the MSAB are presented (IPHC-2017-MSAB10-08), and the paper finishes with a discussion of ideas on how the catch may be distributed across the coast (IPHC-2017-MSAB10-10).

GOALS, OBJECTIVES, AND PERFORMANCE METRICS

Defining goals and objectives is a necessary part of a management strategy evaluation (MSE) which should be revisited often to make sure that they are inclusive and relevant. The MSAB has developed six goals with multiple objectives for each (**Error! Reference source not found.**). Performance metrics can b e developed from the goals and objectives by defining a measurable outcome, a probability (i.e., level of risk), and time-frame over which it is desired to achieve that outcome.

GOALS AND OBJECTIVES

The goals and objectives include

- biological sustainability,
- fishery sustainability, access, and stability,
- minimize discard mortality,
- minimize bycatch and bycatch mortality,

- serve consumer needs, and
- preserve biocomplexity.

These goals continue to be defined and developed.

PERFORMANCE METRICS

IPHC-2017-MSAB09-08 Rev_2 presented thirteen performance metrics associated with the current goals and objectives, presented in terms of risk. Appendix A presents a summary of the measurable objectives and associated performance metrics.

FRAMEWORK

The framework of the closed-loop simulations is a map to how the simulations are performed (Figure 2). There are four main modules to the framework:

1. The **Operating Model (OM)** is a representation of the population and the fishery. It simulates the numbers-at-age, accounting for mortality and any other important processes. It also incorporates uncertainty in the processes and may be composed of multiple models to account for structural uncertainty.
2. **Monitoring (data generation)** is the code that simulates the data from the operating model that is used by the estimation model. It can introduce variability, bias, and any other properties that are desired.
3. The **Estimation Model (EM)** is analogous to the stock assessment. Using the data generated, it produces an annual estimate of stock size and status and provides the advice for setting the catch levels for the next time step. However, simplifications may be necessary to keep simulation times within a reasonable duration.
4. **Management Procedure** is the application of the estimation model output along with the scale and distribution management procedures (Figure 1) to produce the catch limit for that year.

OPERATING MODEL

For the simulations to investigate a coastwide fishing intensity, the stock synthesis (Methot and Wetzel 2013) assessment software was used as an operating model. This platform is currently used for the stock assessment, and the operating model was comprised of the two coastwide assessment models (short and long time-series) currently used in the ensemble. For future MSE evaluations (in particular, investigating the Distribution component of the harvest policy) a more complex operating model will be developed that can provide outputs by defined areas or regions and can account for migration between these areas. This model has been referred to as a multi-area model.

The current stock assessment ensemble, composed of four different assessment models, includes a cross between coastwide or fleets-as-areas structuring of the data, and the length of the time series. Using a areas-as-fleets model would require generating data and distributing catch to four areas of the coast, which would involve many assumptions. In addition, without a multi-area model, there would not be feedback from migration and productivity of harvesting in different areas. Therefore, only the two coastwide models were used, but with additional variability. These models are structured to use five general sources of removals (these are aggregated for modelling purposes and do not correspond to specific fisheries or sectors): the directed commercial halibut fishery (including research landings), commercial discard mortality (previously known as wastage), bycatch (from non-halibut-target fisheries), recreational, and subsistence. The TCEY was distributed to each source in an ad hoc manner using current available information (see below).

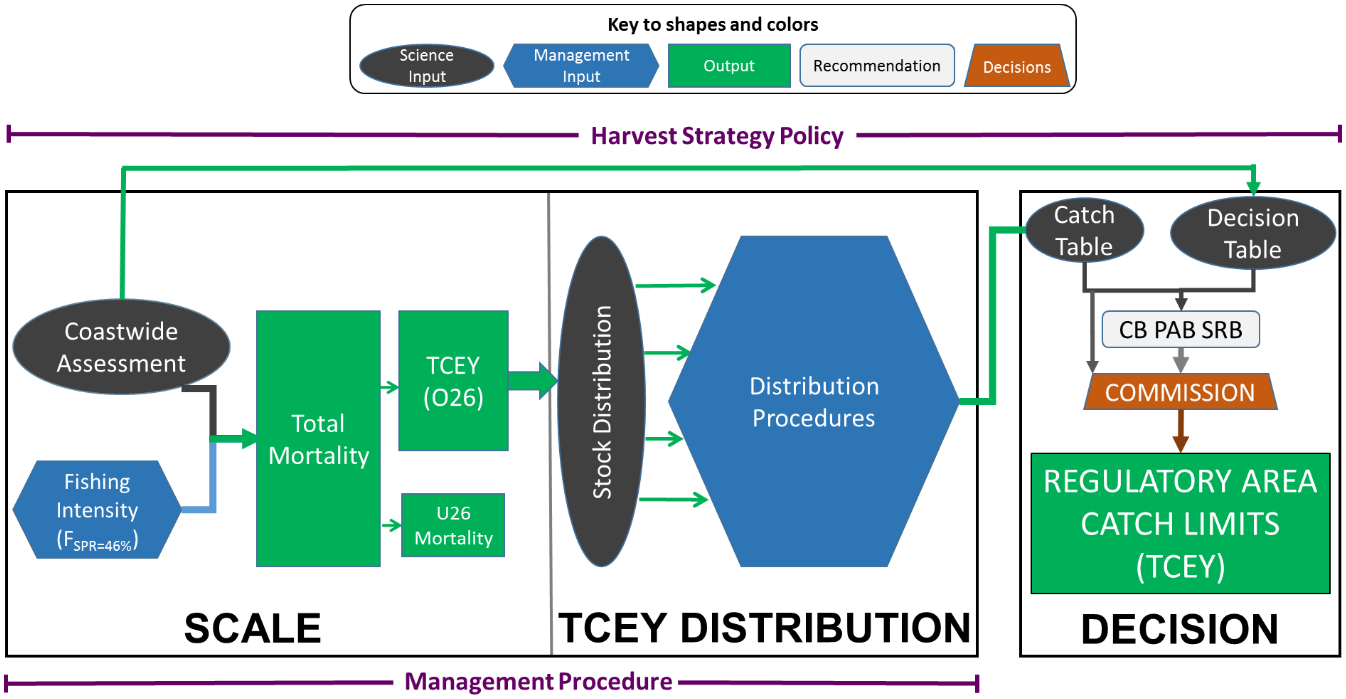

Figure 1: A pictorial description of the interim IPHC harvest strategy policy showing the separation of scale and distribution of fishing mortality. The "decision step" is when policy and decision making (not currently part of the management procedure) influences the final mortality limits.

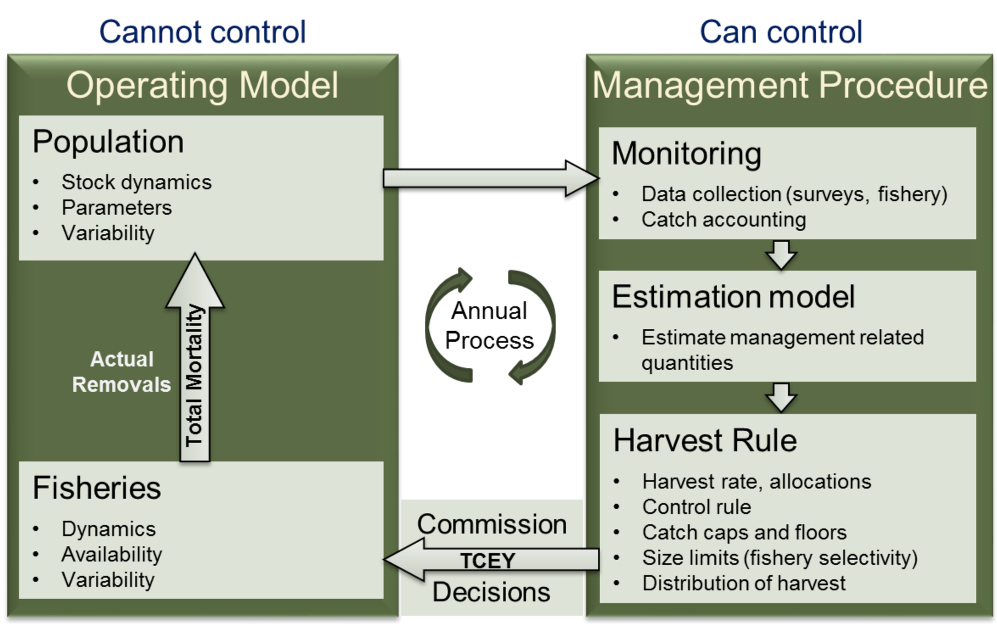

Figure 2: Diagram of the relationship between the four modules in the framework. The simulations run each module on an annual time-step, producing output that is used in the next time-step. See text for a description of operating model, monitoring, estimation model, and harvest rule.

MONITORING (DATA GENERATION)

An estimation model was not used due to time constraints; thus, no data were generated.

ESTIMATION MODEL

An option called “Perfect Information” was used in these simulations, which assumes that the population values needed to apply the harvest rule are exactly known (e.g., spawning biomass, stock status, etc.). This option is useful as a reference to the performance without the additional uncertainty of an estimation model. Perfect Information is a best-case scenario and introducing an estimation model will most likely increase variability, and therefore likely the risk in most performance metrics, sometimes in an unpredictable way.

An estimation model will be considered for future simulations, but due to time-constraints, was not used here.

MANAGEMENT PROCEDURE

The management procedure evaluated is shown in Figure 1, but focused on the Scale portion. In addition to F_{SPR}, points in a control rule to adjust the fishing intensity at low stock status were examined (discussed below). For these simulations, the two coastwide models were used, thus mortality only needed to be distributed to the five coastwide sources of mortality (directed commercial, discard mortality, bycatch, recreational, and subsistence).

SUMMARY OF THE FRAMEWORK

A summary of the major specifications for each component is provided below, with the components listed in a specific order where the next component is dependent on the decisions for the previous components.

1) Operating Model
    a) Stock synthesis, based on coastwide assessment models (short and long models).
    b) Five sources of mortality (commercial, discard mortality, bycatch, recreational, and subsistence).
    c) Uncertainty incorporated through parameter uncertainty and model uncertainty.
2) Management Procedure
    a) A coastwide fishing intensity, SPR, which defines F_{SPR}.
    b) A limit point, where fishing is set to zero, and a threshold point, below which fishing intensity decreases in the harvest control rule.
    c) Mortality assigned to source based on historical information (with variability)
3) Estimation Models
    a) Perfect Information (as a reference if we knew population values exactly when applying the harvest rule).
4) Data Generation
    a) Not needed at this time.

SCENARIOS AND UNCERTAINTY

Scenarios are alternative states of nature in the operating model, which are represented by parameter and model uncertainty. These alternative states of nature integrate over the uncertainty in the system that we cannot, or choose not to, control. The scenarios for the MSE simulations include uncertainty in the operating model processes as described in Table 1.

Table 1: Processes and associated uncertainty included in the operating model (OM). TM refers to total mortality.

Process	Uncertainty
Natural Mortality (M)	Estimate appropriate uncertainty when conditioning OM
Recruitment	Random, lognormal deviations with a standard deviation of 0.6
Size-at-age	Annual and cohort deviations in size-at-age with bounds
Steepness	Estimate appropriate uncertainty when conditioning OM
Regime Shifts	Autocorrelated indicator based on properties of the PDO for regime shift
TM to source	See section on allocating TM to sectors
Proportion of TCEY	Source specific. Sum of mortality across sources may not equal coastwide TM

ALLOCATING SIMULATED TOTAL MORTALITY TO SOURCE

The simulated management strategy returns a coastwide TCEY, which is then allocated to each of the five sources, with variability. In reality, there is a slight difference between the Total Mortality (TM) and the TCEY because of shortfalls and overages, but those should be dealt with on a source-specific basis. The MSAB09 meeting in May 2017 noted that the history of removals, in conjunction with uncertainties and sensitivities, can be used to allocate TM to each sector. Recent mortality or proportions of TM for each source were used to guide the allocation using relationships between the sources, or proportions of the TM.

A summary of the methods used to allocate total mortality to the five sources is provided in Table 2. Additional details can be found in IPHC-2017-MSAB10-09.

Due to specified minimum levels of subsistence and bycatch mortality, as well as random variability, it is possible that, at low levels of total mortality, there is no directed commercial mortality and that the actual total mortality exceeds the mortality determined from the management procedure. Expected values of the mortality and proportion by source plotted against Total Mortality is shown in Figure 7.

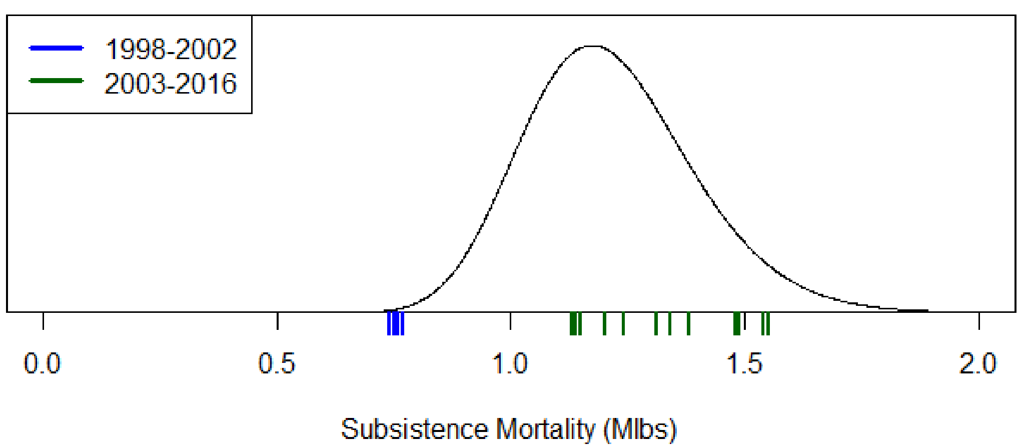

Figure 3: The lognormal distribution used to randomly generate subsistence mortality. Shown as blue and green tick lines at the bottom are the observed subsistence mortality (Mlbs) from 1998-2002 (blue) and 2003-2016 (green).

Table 2: A summary of the methods to allocate total mortality to each of the five sources used in the operating model.

Source	Method of allocating Total Mortality
Subsistence	Randomly drawn from a lognormal distribution with a median of 1.2 M lbs and a coefficient of variation (CV) of 15%. The 5th and 95th percentiles are approximately 0.9 and 1.5 M lbs, respectively, and the distribution with historical mortality is shown in Figure 3.
Bycatch	The non-directed component of the total mortality is randomly drawn from a lognormal distribution with a median of 7.0 M lbs and a CV of 20%. The 5th and 95th percentile are approximately 5.0 M lbs and 9.7 M lbs, respectively, and the distribution with historical mortality is shown in Figure 4.
Recreational	The percentage of recreational mortality was linearly decreasing with total mortality when the total mortality was less than 57 M lbs. The recreational mortality was randomly drawn from a lognormal distribution with a median of 7.7 M lbs and a CV of 20% when the total mortality was greater than 57 M lbs. Figure 5 shows the simulated distribution of recreational mortality at different levels of total mortality, and the recreational mortality proportion of total mortality at different levels of total mortality. Also shown are the historical observations.
Discard Mortality	The discard mortality was modelled as a function of the commercial plus discard mortality (total mortality minus subsistence, bycatch, and recreational mortality) and the size at age 8 for a male Pacific halibut (smaller fish likely results in more discard mortality). Figure 6 shows the simulated discard mortality as a proportion of the commercial plus discard mortality for various levels of commercial plus discard mortality and size at age 8 for a male Pacific halibut.
Commercial	The commercial mortality is the remainder of the total mortality after subtracting the subsistence, bycatch, sport, and discard components.

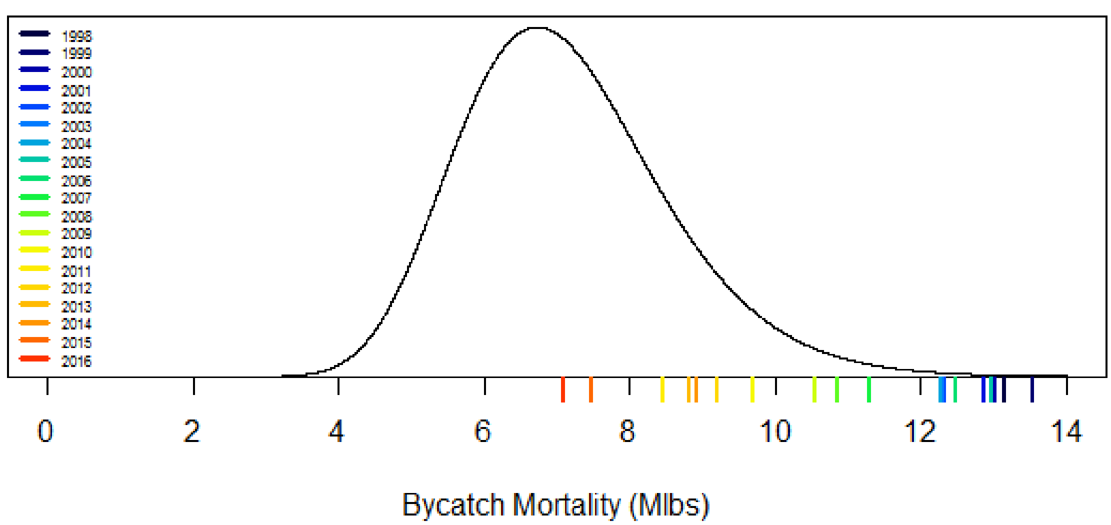

Figure 4: The lognormal distribution from which bycatch mortality is randomly drawn along with observed bycatch mortality since 1998. The colors represent years of the observations, starting with dark blue for 1998 moving to red in 2016.

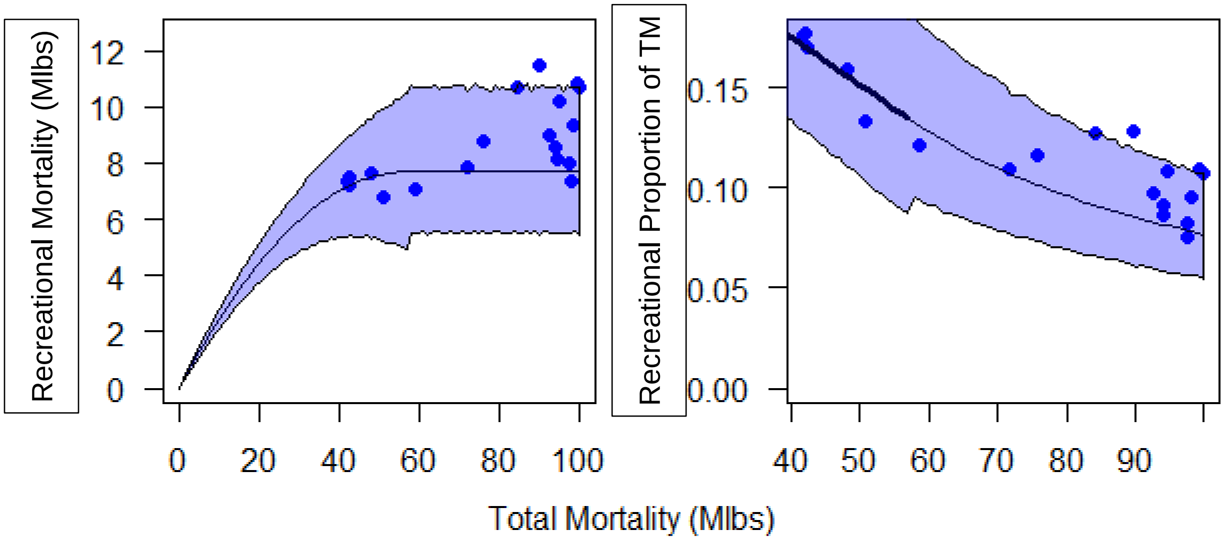

Figure 5: Simulated and observed recreational mortality (left) and the recreational proportion of the total mortality (right) with the area between the 5th and 95th quantiles shown in light blue.

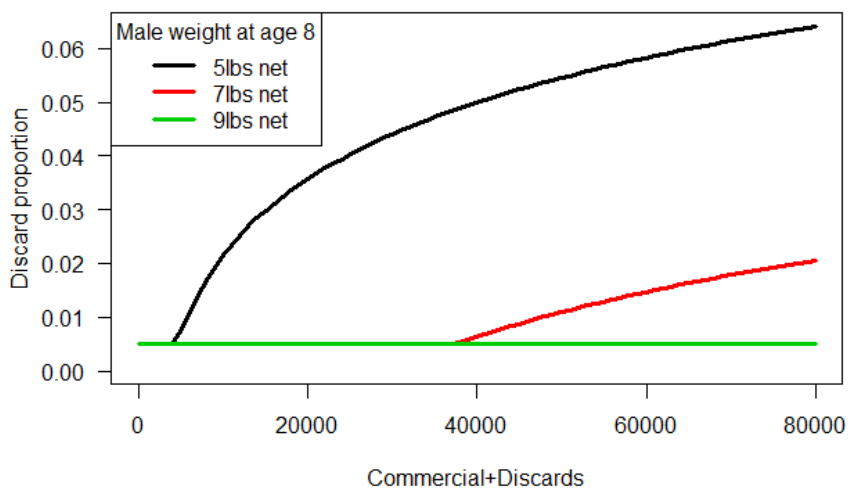

Figure 6: The discard proportion used to allocate discards as a function of commercial+discards and three different values of male weight at age 8.

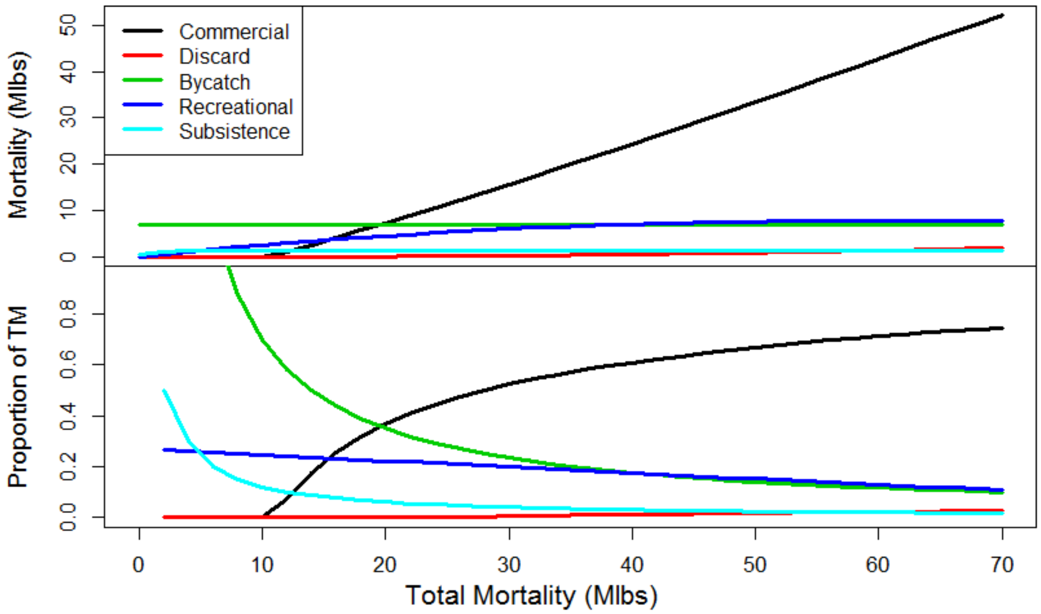

Figure 7: Average sector specific mortality (top, Mlbs) and the sector-specific proportion of Total Mortality (TM) plotted against TM. For plotting purposes, age 8 males are 6 lbs and random variability is not included.

SIMULATING WEIGHT-AT-AGE

It is important to simulate time-varying weight-at-age because it is a very influential contributor to the yield and status of Pacific halibut. There are 82 years of weight-at-age observations in the long time-series assessment models, with an observed wide range over the years (Figure 8 and Figure 9). Many years of these data have been estimated from sparse data, and the entire time-series has been smoothed to eliminate large deviations from year to year.

Important behaviors of the historical weight-at-age time-series to consider when simulating future weight-at-age are

1. the age-specific weights-at-ages tend to increase and decrease in the same year (little evidence of lags due to specific cohort effects; Figure 8 upper plot),
2. the time-series appears to be similar to a random walk with smooth trends and few large jumps in observations (partly due to the smoothing that was done; Figure 8), and
3. there appears to be some ages that do not strictly follow the general trend (evident at the end of the time series where the sampling was likely greater; Figure 8 lower plot).

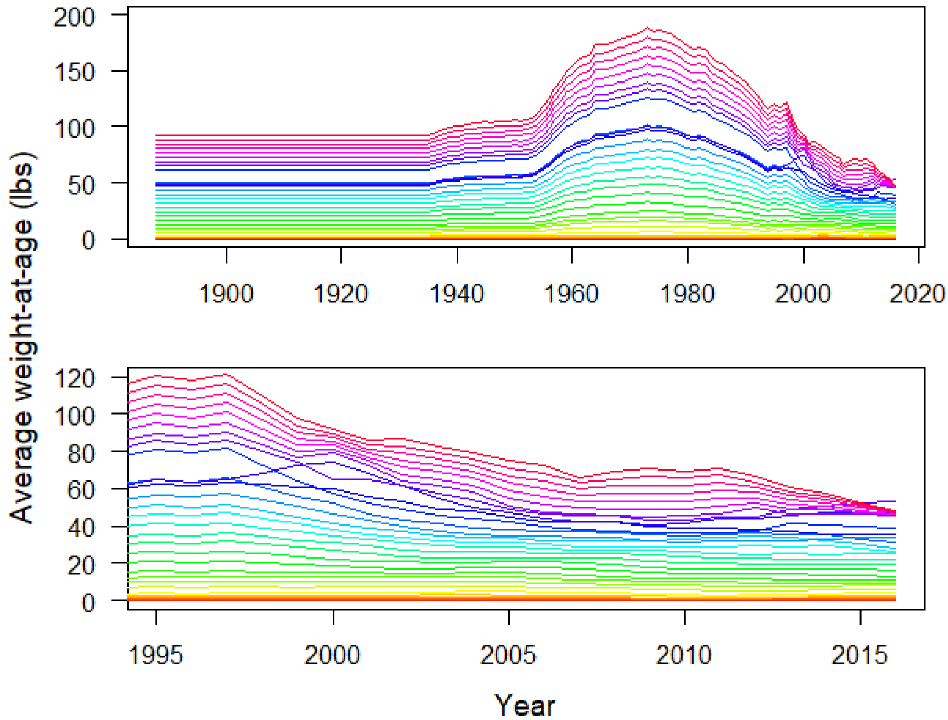

Figure 8: Historical weight-at-age as used in the long time-series assessment models. Note that the observations are smoothed over years to reduce the effect of observation error.

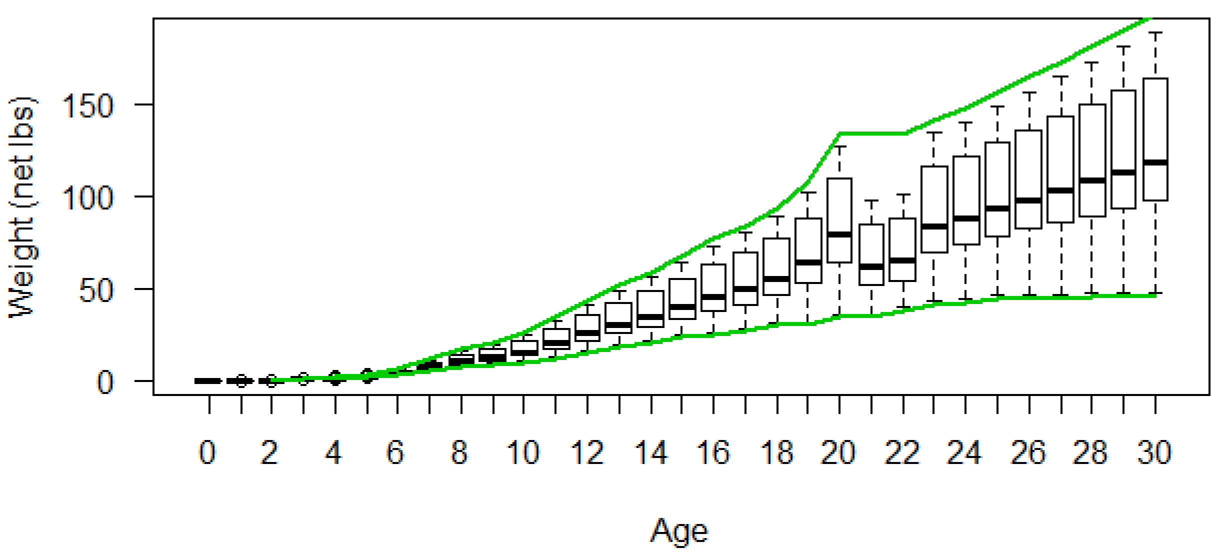

Figure 9: Boxplots of weight at ages 0 to 30 over all historical years. The green line shows the lower and upper bounds used in the simulations.

The method used to simulate weight-at-age addressed each of these behaviors in the following ways.

1. A single deviation was generated from a normal distribution with a constant standard deviation (0.05), and was a multiplier on the current year's weight-at-age to determine the weight-at-age in the next year. This made all weights for each age increase or decrease similarly.
2. A random walk was used where the weight-at-age in the next year was generated from the weight-at-age in the current year. The deviation in (1) was also correlated with past deviations to simulate periods of similar trends (ρ=0.5).
3. Deviations for each age 6 and greater were generated from a normal distribution with a constant coefficient of variation for each age (0.01), resulting in standard deviations scaled by the mean weight-at-age observed over all historical years with observations. This allows for larger deviations for older fish and provides a mechanism for the mean weight of a specific age to depart from the overall trend simulated in step 1.

The random walk could potentially traverse to extremely high values or low values (obviously negative weight-at-age is not valid). Therefore, boundary conditions were set to limit the range over which weight-at-age could vary. The boundary limits were determined from the observed range of weight at each age, and expanded 5% beyond the minimum and maximum weight at each age observed. Two upper boundaries (ages 21 and 22) were expanded further to equal the upper boundary of age 20 (Figure 9). The random walk simulations remained within the bounds by applying the following algorithm.

1. If a weight-at-age was simulated to be beyond the bounds, the deviations for only the ages where the age-specific bounds were exceeded were reduced by one-half and applied again to determine if it still exceeded the bounds.
2. Repeat step (1) until no age-specific bounds were exceeded.

Example simulated weight-at-age time series are shown in Figure 10 and Figure 11.

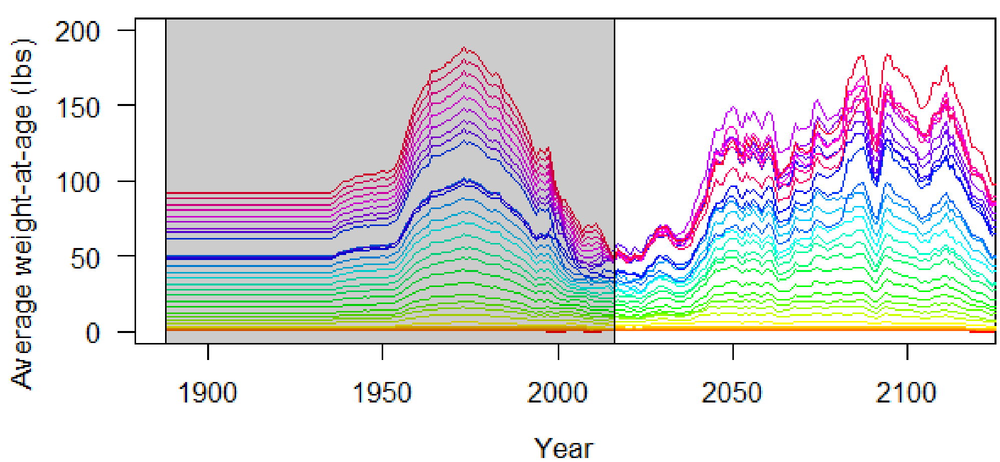

Figure 10: One potential simulated female weight at age (2017-2116). The historical period is shown for reference (1888-2016).

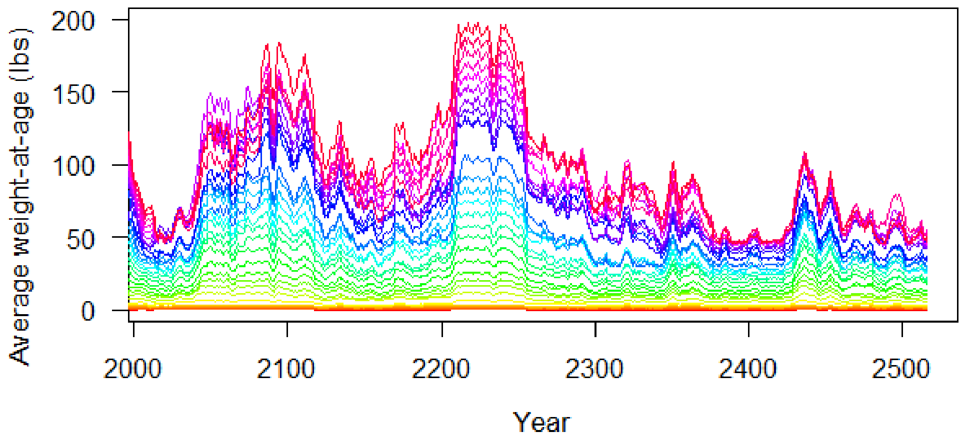

Figure 11: One potential simulation of female weight-at-age for 500 years.

SIMULATING REGIME SHIFTS

An environmental regime is used in the stock assessment to determine if average recruitment is high or low. This is based on the pacific Decadal Oscillation (PDO, http://research.jisao.washington.edu/pdo/, Mantua et al. 1997, Figure 12) and the value is 0 or 1 depending on classified cool or warm years, respectively (Figure 13).

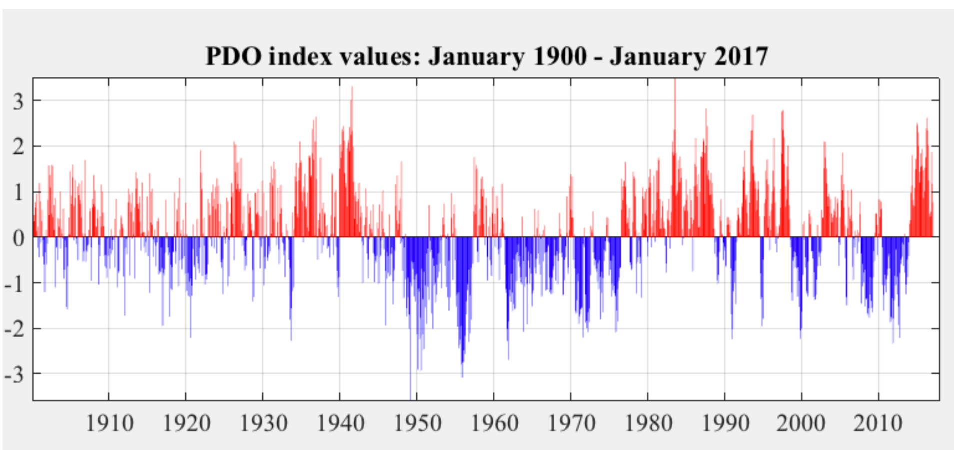

Figure 12: Pacific Decadal Oscillation (PDO) (figure from http://research.jisao.washington.edu/pdo/).

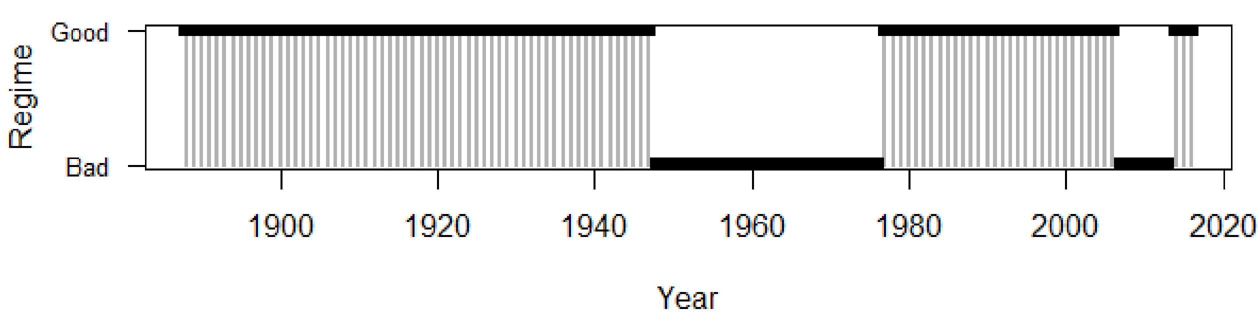

Figure 13: Good and bad regimes used in the Pacific halibut stock assessment for 1888-2016.

The regime was simulated in the MSE by generating a 0 or 1 to indicate the regime in that future year. To encourage runs of a regime between 15 and 30 years (an assumption of the common periodicity, although recent years have suggested less), the environmental index was simulated as a semi-Markov process, where the next year depends on the current year. However, the probability of changing to the opposite regime was a function of the length of the current regime with a probability of changing equal to 0.5 at 30 years, and a very high probability of changing at 40 years.

The simulated length of a regime was most often between 20 and 30 years, with occasional runs between 5 and 20 years.

Some Additional Sources of Uncertainty Not Currently Considered

Some sources of uncertainty that were not considered, but will likely be considered in the future are:

Selectivity: It may be desirable for the time-varying selectivity for at least commercial gears to be linked to changes in weight-at-age.

Migration: Migration will require a multi-area model and hypotheses about movement. A multi-area model is being developed with four regions. Migration hypotheses will be informed by tagging data as well as other observations from various fisheries and surveys.

Conditioning the Operating Model

The operating model (OM) should be a reasonable depiction of reality with an appropriate level of uncertainty. The OM consists of two stock synthesis (Methot and Wetzel 2013), models parameterized similarly to the short and long coastwide assessment models for Pacific halibut (Stewart 2015 appendix of RARA). Each model is conditioned by fitting to the same data used in the 2016 stock assessment (Stewart & Hicks 2017). To evaluate and choose management procedures that are robust to uncertainty in future states of the population, many assumptions in the assessment model were freed up to characterize a wider range of possibilities in the future. Estimating natural mortality for both sexes in both models and estimating steepness were the only changes to estimated parameters from the assessment model when conditioning.

Parameter variability was characterized by randomly sampling parameters for each simulation from a truncated multivariate normal distribution conditioned to data. Unrealistic simulated historical trajectories (e.g., the population could not support the observed catch) were eliminated.

The conditioned OM has a considerable amount of extra variability compared to the ensemble stock assessment (Figure 14). The assessment ensemble contains four individual models while the OM contains only two, which is why the trend at the end of the time series is slightly different, although well within the uncertainty.

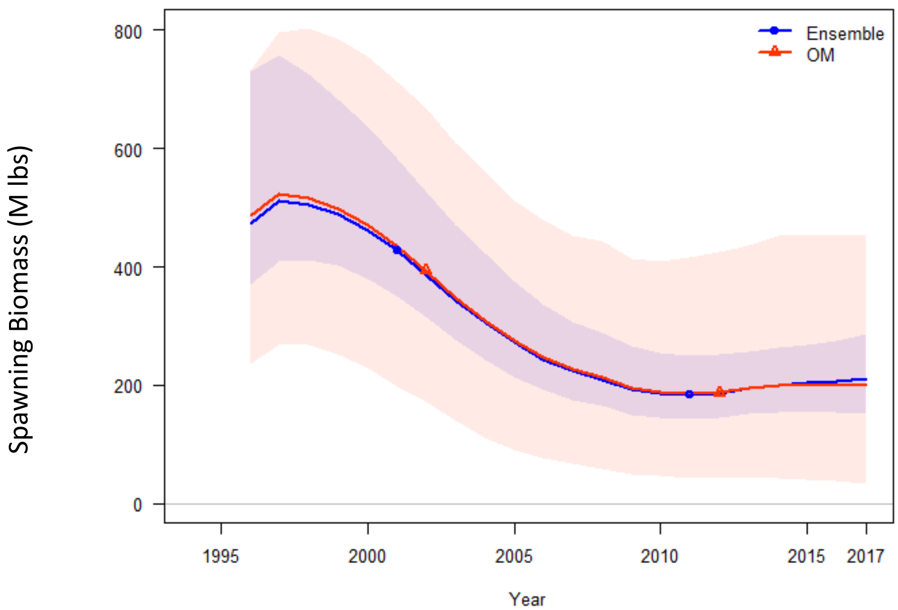

Figure 14: The conditioned operating model (red) compared to the stock assessment ensemble (blue) with 95% credibility intervals.

A potential issue highlighted at SRB11 was that starting the OM in 2017 with such a wide range of uncertainty will not adequately characterize our best knowledge of the near future (short-term) and the medium-term (before long-term equilibrium). However, the long-term results are appropriate since the current state would not have an effect, and the wide range of uncertainty is a result of the chosen uncertainties to evaluate harvest strategies against. One solution to provide short-term results would be to start the OM from the assessment model and its uncertainty (the blue shaded region in Figure 14). However, this may not be indicative of our best predictions for the short-term or medium-term because of the wider range of uncertainty in the parameters that will result in large deviations at the start of the simulations and because the OM is not the best representation of the current state of the population (i.e., the ensemble assessment is with four models).

Instead, we present results for the long-term to identify management procedures that meet the goals and objectives defined by the MSAB. These management procedures can then be further investigated using short-term predictions directly from the assessment model (1-3 years from the end of the time-series; 8-11 years from the most recent information on recruitment) to identify how they may affect the fishery now. For example, the decision table already presents risk metrics for various SPR values, and these results can be used to evaluate the immediate consequences to the fishery of a change in the harvest policy. Additionally, transitory behavior from the short-term to the long-term can be highlighted in future analyses. This may be describing the trends of various trajectories (e.g., catch or spawning biomass) between the short-term or long-term. For example, the short-term may indicate low catches with a higher catch on average in the long-term, but to get there, it appears that catches may be low for a short time before increasing.

The reason that it is difficult to quantify medium-term results is that we have very little predictive power for that time-period. In the short-term, we have an idea of where we currently are and what may occur in the next few years (e.g., we have some data indicating recruitment and weight-at-age). In the long-term, we are summarizing statistics over a wide range of uncertainty and all possible states (we do not need to know anything about the current state of the population). However, that uncertainty is not well described in the medium-term because it is partially dependent on the current state, but also affected by the wide range of possibilities. Therefore. it could be very misleading to present medium term results as unbiased and informative predictions.

SIMULATIONS

The simulations focused on the scale component of the harvest strategy policy (Figure 1) and distributing the TCEY was not necessary because the operating model used only coastwide models. As a result, IPHC Regulatory Area-specific performance metrics cannot be calculated at this time.

MANAGEMENT PROCEDURES

Simulations were used to investigate the fishing intensity in the scale component of the harvest strategy policy. A harvest control rule consists of a procedural SPR, a threshold value, and a limit value (Figure 15). The procedural SPR determines the fishing intensity (F_{SPR}) when stock status (measured from dynamic relative spawning biomass, dRSB) is above a threshold. The threshold is the dRSB where the fishing intensity is reduced if stock status falls below this value. The limit is the point at which fishing is halted if the dRSB is below this value. Dynamic relative spawning biomass (dRSB) is a measure of stock status that measures the effect of fishing on the population by accounting for changing conditions.

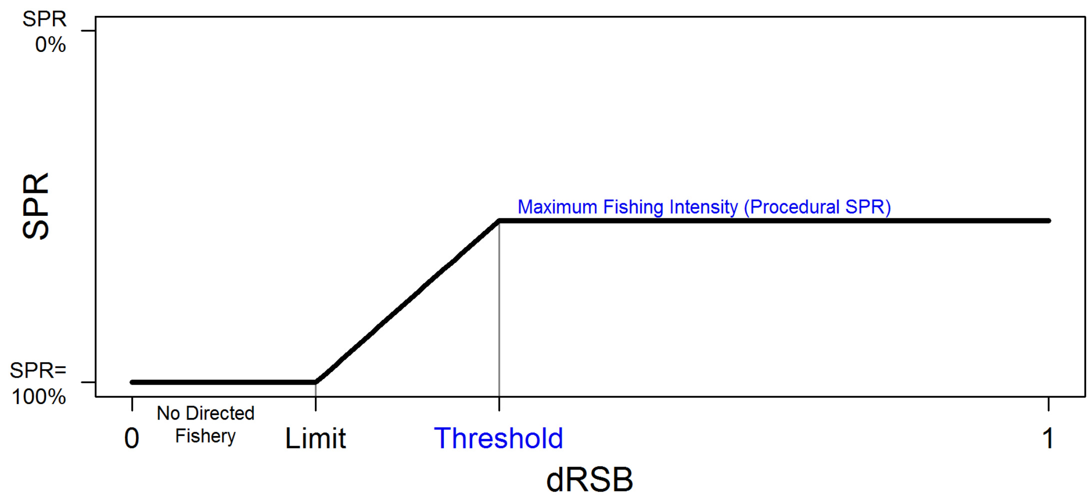

Figure 15: The harvest control rule with stock status (dRSB) on the horizontal axis and SPR (spawning potential ratio) on the vertical axis (determining fishing intensity, F_{SPR}). Note that the SPR values on the vertical axis range from 100% at the bottom to 0% at the top to indicate increasing fishing intensity. Fishing intensity decreases when stock status is below the threshold point, and fishing is halted when stock status is less than the limit point. Items in blue were evaluated in these simulations.

The procedural SPR and the threshold value of the harvest control rule were the focus for evaluation. A ceiling (maximum) on total mortality and a floor (minimum) on total mortality were also evaluated, but are not reported in this document. Table 3 lists the specific values of the elements of the management procedure that were investigated.

Table 3: Recommendation from MSAB09 (paragraph 28 of IPHC-2017-MSAB09-R) of elements of the management procedure to evaluate.

Element of the Management Procedure	Values
Procedural SPR	0.25 – 0.60, higher density near 46%
Control Points (thresholds:limits)	30:20, 40:20
Ceiling on Total Mortality	85 Mlbs
Floor on Total Mortality	30 Mlbs

RESULTS

Results from the simulations are presented in relation to two goals: 1) biological sustainability, and 2) fishery sustainability, stability, and access (see Appendix A). Many performance metrics were developed, but only performance metrics identified as important to MSAB members and directly related to the current goals and objectives were reported. Performance metrics related to the goals of minimizing discard mortality, minimizing bycatch, and preserving biocomplexity were not reported since the modelling did not provide adequate feedback in the simulation of these concepts. These goal and objectives will be addressed in future analyses.

Performance metrics are reported as a probability, a median average, or an average annual variability (AAV; Table 4 and Table 5). When a performance metric is reported as a probability, it can thought of as the probability that the event occurs in the final year of the simulation (i.e., long-term). An alternative probability not reported here (although useful) was the probability that an event occurred in any one of ten years, when the stock is at equilibrium (i.e., long-term). This alternative probability will be reported in the future after further refinement of the details. A “median average” performance metric provides a measure of an absolute value, and is determined by calculating the average of the last ten years for each simulation and then finding the median of these averages. The averages from each simulation form a distribution from which any summary statistic can be calculated. Finally, the average annual variability is a measure of the average annual change in the catch and is determined by calculating the change in catch between each year in a ten-year period and dividing by the average catch over that same period. It is also a distribution across simulations and can be summarized by any statistic (most commonly the median).

Four performance metrics were reported for the biological sustainability goal. The median average dynamic relative spawning biomass (dRSB), the median average number of mature females in millions, the probability that dRSB is less than 20%, and the probability that dRSB is less than 30%. The reference points 20% and 30% were used because they match the current limit and threshold points, and objectives of avoiding very low stock sizes (20%) and low stock sizes (30%) were stated during the development of the previous harvest policy. However, these target reference points may be updated in future iterations of this process.

Ten performance metrics were reported to reflect fishery objectives. The median average total mortality and median average FCEY (defined here, for simplicity, as all removals except bycatch) were calculated coastwide. What is labeled FCEY here is not the true FCEY, as each Regulatory Area has a very specific definition of FCEY, but it is a proxy including commercial, discard, recreational, and subsistence mortality. The 10^{th} and 90^{th} percentiles of the total mortality were reported to provide insight into the variability. The probability of no commercial mortality is also reported and can be a result of the stock status being below the limit or the total mortality being at a low level such that there is not enough for the commercial fishery after allocating to other sectors. The probability that the FCEY is less than 50.6 M lbs (22,592 mt) was also reported, where 50.6 M lbs is 70% of the average from 1993–2012 (72.25 M lbs; 32,772 mt). The probability that the total mortality decreases by more than 15% from the previous year measures the chance of a large decrease. Finally, three statistics for the average annual variability (AAV) measure the median average annual change in total, FCEY, and commercial mortalities.

An additional metric not related to any of the goals was the realized SPR. This metric reports the median average SPR and can be different than the procedural SPR due mostly to the reduction in fishing intensity when stock status is less than the threshold value in the harvest control rule, but a small part is due to variability in the sources of mortality.

The performance metrics related to biological sustainability show higher relative spawning biomass as SPR increases (i.e., fishing intensity decreases; Table 4 and Figure 16 panel a), but less change at lower SPR because the stock status is often below the threshold where the SPR is reduced. The realized SPR shows the same pattern (Table 4 and Figure 16 panel d). The effect of the control rule is also seen with a higher dRSB at lower SPR when using the 40:20 control rule, but similar dRSB at higher SPR’s since the control rule would rarely be invoked at these higher SPR’s (lower fishing intensities (Table 5 and Figure 16 panel a). With a control rule, as the target SPR declines, the realized SPR levels off at a minimum value (Table 4 and Figure 16, panel d).

Performance metrics related to fishery sustainability show that yield, both in terms of total mortality (TM) and FCEY (all mortality minus bycatch), is similar across values of SPR between 25% and 40%, but declines at higher values of SPR (i.e., lower fishing intensity; Figure 17). The maximum median average total mortality is around 40 million pounds, but the variability from the simulations show that total mortality commonly ranges from less than 20 million pounds to over 80 million pounds. The variability in total mortality is influenced by uncertainty in the population parameters (e.g., natural mortality) as well as variation in weight-at-age and recruitment.

The median average FCEY was less than 34 M lbs for the range of SPR’s and control rules simulated, thus the probabilities of being less than 50.6 M lbs (70% of the 1993-2012 benchmark FCEY) is greater than 65%. The range of years used for this benchmark represent a period of time with high weight-at-age and some extremely large recruitment events, and is atypical of average conditions.

The variability in yield is represented with a number of performance metrics (Figure 16 panel c, Table 4, and Table 5). A decrease in the total mortality from one year to the next of greater than 15% was more likely at low SPRs (more often below the stock status threshold) and ranged from 24% at an SPR of 25% to 3% at an SPR of 60%. The probability of a large decrease was less at an SPR of 30% with a threshold of 40% compared to a threshold of 30% because the ramp of the harvest control rule was shallower. The average annual variability (AAV) showed that the minimum variability in total mortality that is likely to be achieved with these management procedures is around 6%. However, the trade-off between variability and yield becomes apparent at an SPR of 30%, where a slight increase in yield results in a nearly doubling of yield variability (Figure 16, panels b and c). The AAV for FCEY and commercial catch was greater than for total mortality.

Table 4: Performance metrics determined from outputs of the closed-loop simulations for various fishing intensities indicated by a procedural Spawning Potential Ratio (SPR) and a 30:20 threshold:limit in the harvest control rule.

	30:20 Threshold:Limit										
	High Fishing Intensity										**Low Fishing Intensity**
Procedural SPR	**25%**	**30%**	**40%**	**42%**	**44%**	**46%**	**48%**	**50%**	**55%**	**60%**	**100%**
Median average realized SPR	39%	39%	42%	44%	46%	47%	49%	51%	56%	61%	93%
Biological Sustainability											
Median average dRSB	29%	29%	34%	36%	38%	41%	43%	45%	50%	56%	92%
Median Average # of Mature Females (million)	5.87	5.97	6.73	6.98	7.19	7.59	7.91	8.03	9.01	9.75	13.63
P(dRSB<20%)	3%	3%	3%	2%	2%	2%	2%	2%	1%	1%	0%
P(dRSB<30%)	78%	64%	19%	13%	10%	7%	6%	5%	3%	2%	0%
Fishery Sustainability											
Median average Total Mortality (M lbs)	40.09	39.56	39.91	37.62	35.27	36.37	34.71	35.50	33.48	32.72	7.63
10^{th} & 90^{th} percentiles TM (M lbs)	13 113	13 126	13 109	13 101	14 98	13 99	13 90	13 91	13 82	12 75	7 8
Median average FCEY (M lbs)	32.86	32.69	32.72	30.76	28.31	29.23	27.57	28.14	26.33	25.38	0.50
P(No Commercial)	11%	9%	8%	8%	7%	8%	8%	8%	8%	10%	100%
P(FCEY < 50.6 M lbs)	69%	66%	69%	69%	72%	73%	74%	74%	77%	80%	100%
P(decrease TM > 15%)	24%	17%	6%	5%	5%	5%	5%	4%	4%	3%	27%
Median catch variability (AAV of TM)	19%	13%	7%	7%	6%	6%	6%	6%	6%	6%	20%
Median catch variability (AAV of FCEY)	25%	17%	10%	10%	10%	10%	10%	10%	10%	10%	17%
Median catch variability (AAV of Commercial)	34%	23%	13%	13%	14%	13%	14%	14%	14%	14%	0%

Table 5: Performance metrics determined from outputs of the closed-loop simulations for various fishing intensities indicated by a procedural Spawning Potential Ratio (SPR) and a 40:20 threshold:limit in the harvest control rule.

	40:20 Threshold:Limit										
	High Fishing Intensity										**Low Fishing Intensity**
Procedural SPR	**25%**	**30%**	**40%**	**42%**	**44%**	**46%**	**48%**	**50%**	**55%**	**60%**	**100%**
Median average realized SPR		44%	46%			48%		51%		61%	93%
Biological Sustainability											
Median average dRSB		37%	39%			41%		45%		56%	92%
Median Average # of Mature Females (million)		6.92	7.38			7.67		8.32		9.60	13.63
P(dRSB<20%)		1%	1%			1%		2%		1%	0%
P(dRSB<30%)		3%	3%			3%		3%		2%	0%
Fishery Sustainability											
Median average Total Mortality (M lbs)		39.00	38.57			34.78		34.51		29.27	7.63
10^{th} & 90^{th} percentiles TM (M lbs)		13 108	14 109			13 96		13 95		12 80	7 8
Median average FCEY (M lbs)		31.75	31.52			27.65		27.26		22.31	0.50
P(No Commercial)		9%	7%			8%		8%		10%	100%
P(FCEY < 50.6 M lbs)		68%	69%			73%		72%		80%	100%
P(decrease TM > 15%)		12%	8%			6%		4%		3%	27%
Median catch variability (AAV of TM)		10%	8%			7%		6%		6%	20%
Median catch variability (AAV of FCEY)		14%	12%			11%		10%		10%	17%
Median catch variability (AAV of Commercial)		19%	16%			14%		13%		15%	0%

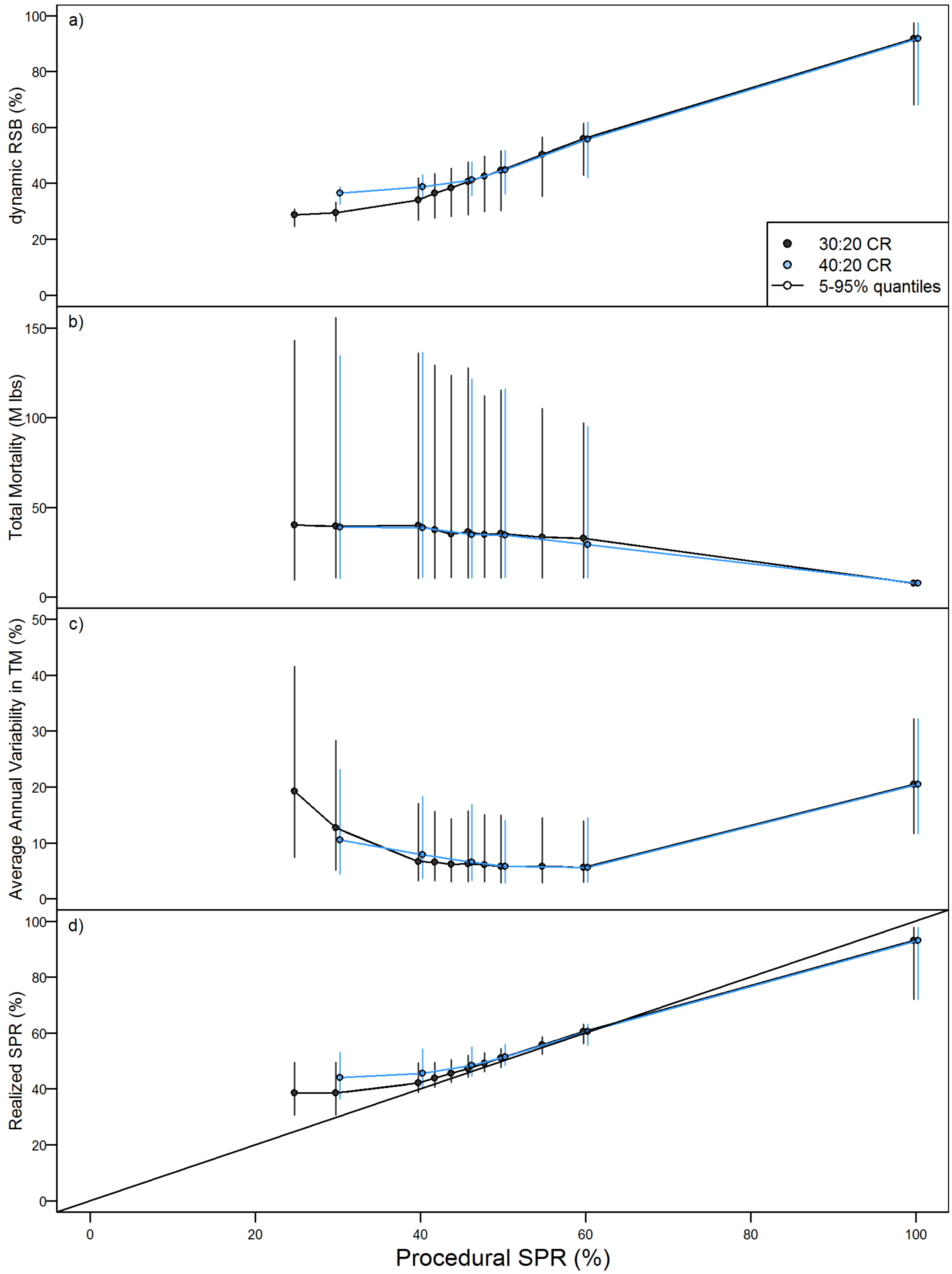

Figure 16: Performance metrics plotted against the procedural SPR (horizontal axis) for different threshold:limit combinations (30:20 in black and 40:20 in blue). Panel a) shows the dynamic relative spawning biomass (biological sustainability goal), panel b) shows the total mortality (fishery sustainability goal), and panel c) shows the average annual variability for total mortality (fishery stability goal). Panel d) shows the realized SPR.

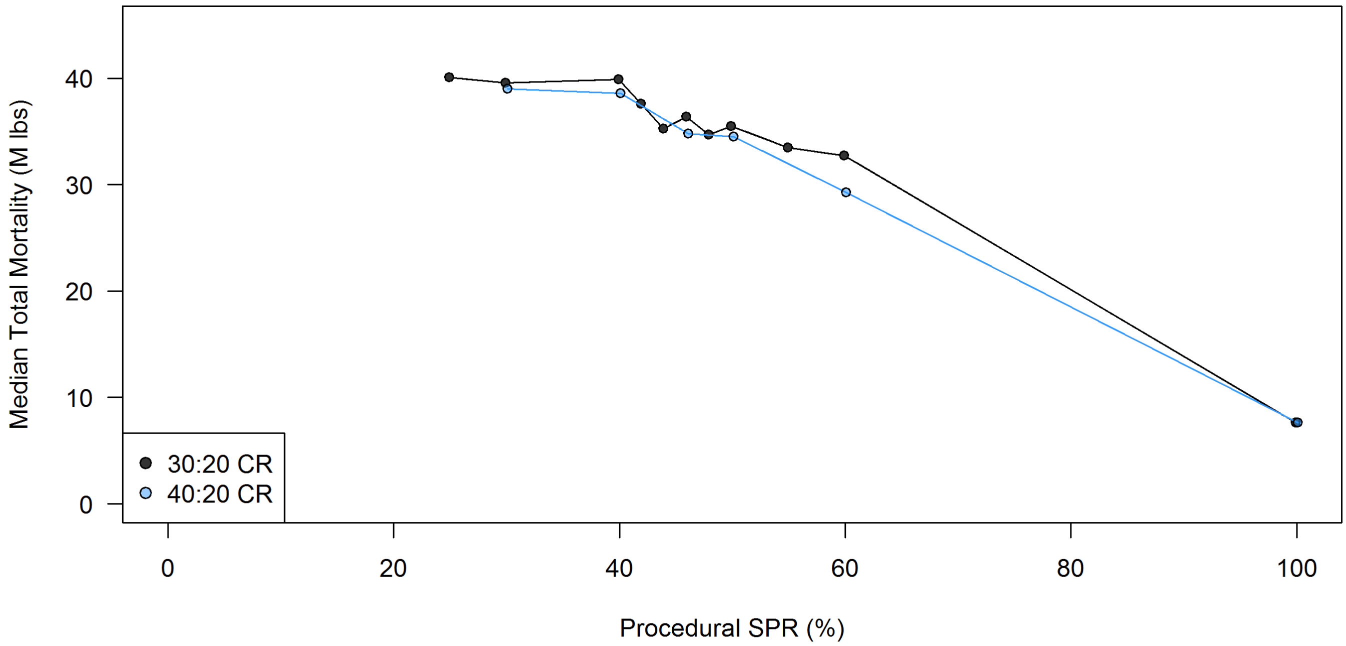

Figure 17: Median average total mortality (M lbs) plotted against procedural SPR for two different threshold:limit combinations (30:20 in black and 40:20 in blue).

Overall, the 46% reference SPR (*status quo* at AM093) is within the range of SPR's that would likely meet the goals and objectives defined by the MSAB. However, an important caveat and caution is that these results use perfect information to determine total mortality from the harvest control rule. Future simulations will incorporate appropriate imperfect information, but insight can be gained from these simulations. For example, the performance of the lowest SPRs (high fishing intensity) will worsen with imperfect information, and it is apparent that variability in yield increases greatly with little gain in yield at SPR values of 30% and lower (Figure 16 and Table 4). Therefore, values of SPR lower than 30% are unlikely to meet fishery stability objectives.

IDEAS ON ESTIMATING STOCK DISTRIBUTION AND DISTRIBUTING THE TCEY

Recommendations from the 93rd IPHC Annual Meeting (AM093) included the following related to distributing TCEY among the Regulatory Areas (IPHC-2017-AM093-R).

> *Para. 30.* ***NOTING*** *that the Commission has indicated its interest in clearer accounting for all mortality, and that Canada has put forward catch limit allocation principles proposing that catch limits include all sources of mortality for each regulatory area, the Commission* ***RECOMMENDED*** *that the presentation of harvest advice be changed to be based on the TCEY… which includes all O26 commercial, sport, personal use/subsistence, bycatch and wastage removals, for the 2018 Annual Meeting cycle, as a step towards more comprehensive and responsible management of the resource that will result in the negotiation of Regulatory Area-specific catch limits based on TCEYs.*

> *Para. 38.* ***NOTING*** *that the term "apportionment" has connotations broader than stock distribution that are not reflective of its meaning in the IPHC context, the Commission* ***RECOMMENDED*** *that it be replaced with the terms "stock distribution" or "stock distribution model(ing)".*

> *Para. 39. The Commission* ***RECOMMENDED*** *that the IPHC Management Strategy Evaluation (MSE) process be accelerated so that more of the elements contained within the current Program of Work are delivered at the 94th Annual Meeting of the Commission in 2018.*

> *Para. 40. The Commission* ***REQUESTED*** *that the IPHC Secretariat initiate a process to develop alternative, biologically based stock distribution strategies for consideration by the Commission and its subsidiary bodies. This should also be incorporated into the MSE Program of Work.*

There is a strong interest in beginning evaluations of the distribution part of the updated harvest strategy policy (Figure 1). Compared to only evaluating the scale component, also evaluating the distribution component increases the complexity of the simulations, involves additional programming, and requires additional stakeholder guidance (i.e., MSAB meetings). The most difficult aspect of accelerating the timeline in the work plan is ensuring that the MSAB is providing the necessary feedback and guidance to the MSE process. Regardless, it has been beneficial to begin the conversation with the MSAB and to begin identifying management procedures related to distributing catch among the Regulatory Areas.

TCEY DISTRIBUTION

TCEY distribution is the management procedure for distributing the TCEY among Regulatory Areas and may be comprised of a purely scientific component to distribute the TCEY in proportion to its estimated biomass in each area (stock distribution) and/or the management component of distributing harvest based on additional considerations (distribution procedures). Stock distribution may be focused on biological areas rather than management areas, and may distribute the TCEY to Regional Areas composed of multiple Regulatory Areas (Figure 18, also see IPHC-2017-MSAB09-09). Changes to that biological distribution and further distributing or allocating the TCEY to individual Regulatory Areas could be different components of the management procedure (Figure 19).

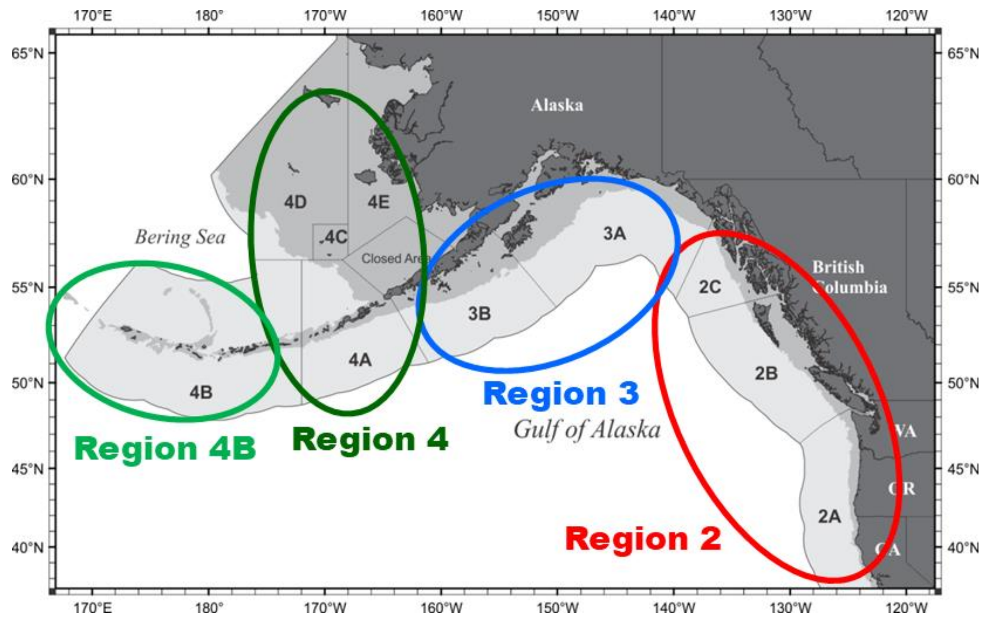

Figure 18: Proposed biological stock distribution Regions.

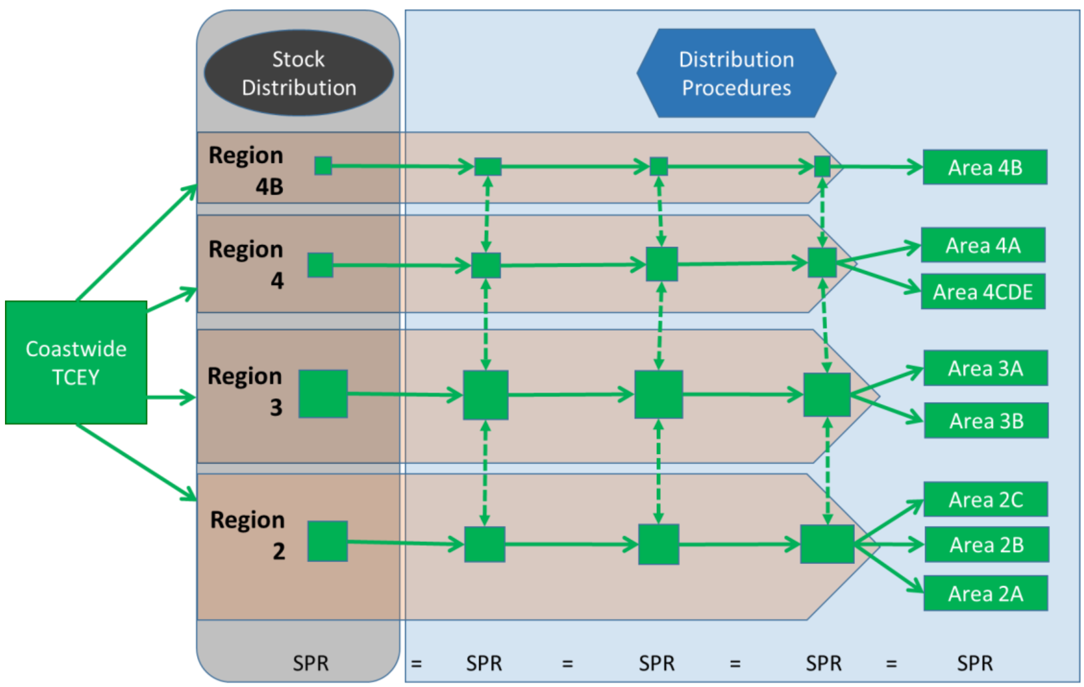

Figure 19: The process of distributing the TCEY to Regulatory Areas from the coastwide TCEY (TCEY distribution in Figure 1). The first step is to distribute the TCEY to regional areas based on the estimate of stock distribution. Following this, a series of adjustments may be made based on observations or social, economic, and other considerations. Finally, the adjusted regional TCEY's are allocated to Regulatory Areas. The allocation to Regulatory Areas may occur at any point after stock distribution and may also be external to the management procedure and instead part of the decision making process (see Figure 1). The dashed arrows represent balancing that is required to maintain a constant SPR, but the allocation step may deviate from the defined SPR.

Stock Distribution

Stock distribution is the analytical process of estimating the proportion of biomass in defined areas of the coast relative to the coastwide biomass. This is a science product and the outcome does not need to specifically align with IPHC Regulatory Areas.

Stock distribution has been determined from the O32 space-time model estimates of the relative proportion of biomass in each Regulatory Area using data from the annual IPHC fisheries-independent setline survey. There may be some disconnect with the TCEY, which is meant to represent the O26 mortality. The SRB agreed (para. 44 of IPHC-2017-SRB10-R) that reporting the estimates of relative proportions using total survey catch may be useful. This may be a better representation of O26 mortality and better align the estimate of stock distribution with the O26 mortality.

Stock distribution may play a role in distributing the TCEY if there is an objective of maintaining a diversity in the population across space. It has been shown that maintaining a diverse portfolio of stocks in salmon populations (e.g., Schindler et al. 2010) has resulted in better resilience to environmental changes and regime shifts, resulting in more sustainable fisheries. Little is known about the exact interplay between geographic regions and, for example, spawning success within the Pacific halibut population, but there may be subtle genetic differences (Drinan et al. 2016) that may make it beneficial to distribute harvest across all the population instead of potentially over-exploiting one component. Additionally, distributing the harvest provides opportunity for many areas. The MSAB agreed (para. 36 of IPHC-2017-MSAB10-R) to consider the definition of biocomplexity and develop objectives related to this goal.

Biocomplexity is linked to biology and therefore not necessarily management areas. Therefore, distributing the O26 mortality among biological regions may be more appropriate than among Regulatory Areas. The MSAB considered a proposal for stock distribution to operate on biological regions (Figure 18) at MSAB10 (para. 35 of IPHC-2017-MSAB10-R). Given the current understanding of Pacific halibut, four biologically relevant regions that meet management needs are: all of IPHC Regulatory Area 2 (called Region 2), all of IPHC Regulatory Area3 (called Region 3), IPHC Regulatory Areas 4ACDE(called Region 4), and Regulatory Area 4B (called Region 4B). Figure 18 shows these four regions in relation to the Regulatory Areas.

These four biologically-based regions capture the broad spatial and productivity domains of the population. Distributing the TCEY among them would continue to protect the geographic life-history variability and possible biodiversity in the Pacific halibut population, but would not force arbitrary delineation among areas with evidence of strong stock mixing. In addition, estimates of the proportion of biomass in each region (Figure 20) would be more stable than estimates for each IPHC Regulatory Area. Further distributing the TCEY to IPHC Regulatory Areas would be done through the distribution procedures component (Figure 19) or as part of the decision making process (Figure 1).

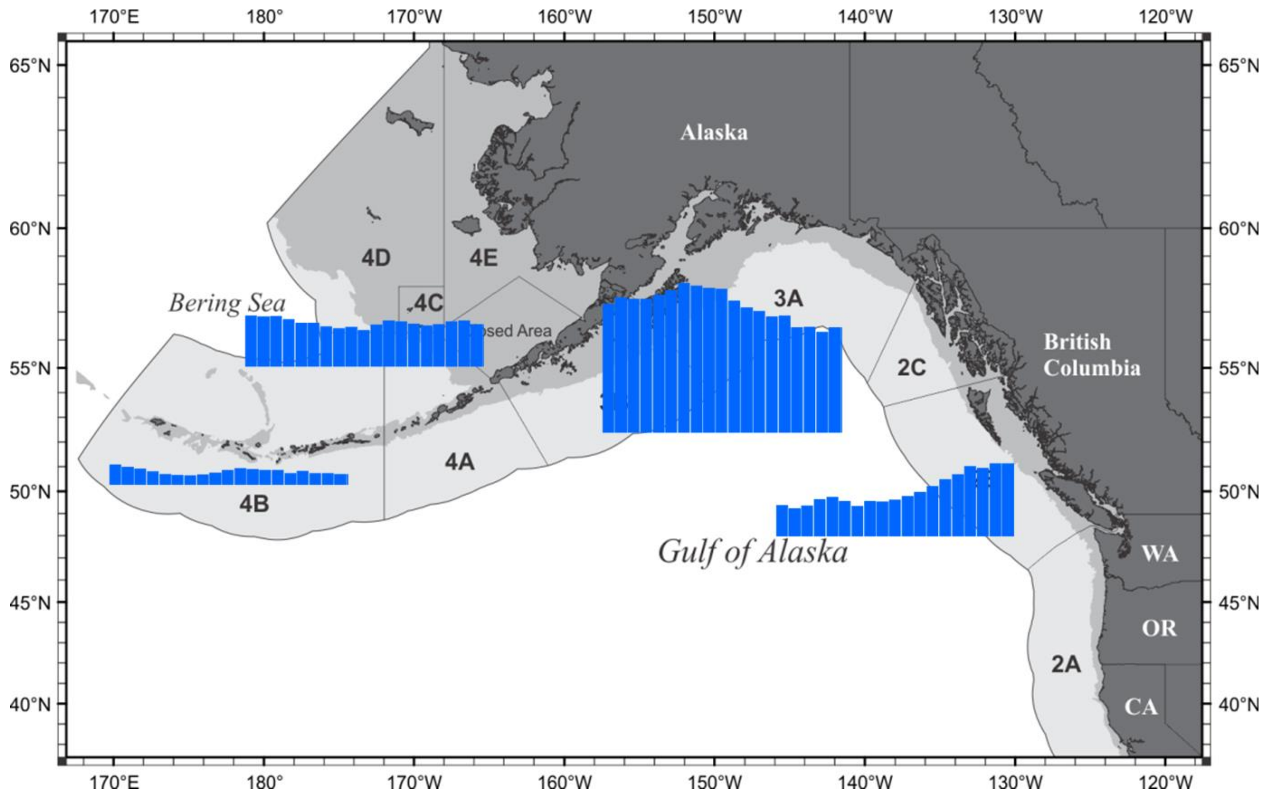

Figure 20: Estimated percentage of the stock in each region (2, 3, 4, and 4B) from 1998–2016. The scale in each region is relative to each other and the four bars from all regions in a particular year sum to one.

Distribution Procedures

The distribution procedures component is the process of further modifying the distribution of the TCEY among regions and then distributing the TCEY among IPHC Regulatory Areas within geographic regions. Modifications at the region or IPHC Regulatory Area level may be based on differences in production between areas, observations in each area relative to other areas (e.g., WPUE), uncertainty of data or mortality in each area, defined allocations, or national shares, for example. Data may be used as indicators of stock trends in each Region or IPHC Regulatory Area, and are included in the TCEY distribution component because they may be subject to certain biases and include factors that may be unrelated to biomass in that Region or Area. For example, commercial weight-per-unit-effort (WPUE) is a popular source of data used to indicate trends in a population and fishery performance, but may not always be proportional to biomass. Types of data that may be used include fishery WPUE, survey observations (not necessarily the setline survey), age-compositions, size-at-age, and environmental observations.

A final step in the distribution of TCEY may be to make further discretionary adjustments, or to simply allocate the TCEY from regional areas to Regulatory Areas based on management decisions (Decision box in Figure 1) that take social, economic, national, and other factors into consideration. The final distribution of TCEY among Regulatory Areas would be input into the stock assessment to determine the adopted SPR and coastwide fishing intensity, which may differ from the procedural SPR due to these final management decisions.

Potential Procedures for Distributing TCEY Across the Coast

The harvest strategy policy begins with the coastwide TCEY determined from the stock assessment and procedural fishing intensity (Figure 1). When distributing the TCEY among regions, stock distribution would likely occur first to distribute the harvest in proportion to biomass, although may occur at a later stage. Adjustments across Regions and Regulatory Area based on TCEY distribution, and the key to these adjustments is that they are relative adjustments such that the overall fishing intensity is maintained (i.e., a constant SPR after each step). Departing from this may be a desired outcome for a particular year (short-term, tactical decision making based on current trends estimated in the stock assessment), but would deviate from the management procedure and the long-term management objectives. Departures from the management procedure may result in undesirable outcomes, but could also take advantage of current situations.

There are many other management procedures that would be worth evaluating as part of the Management Strategy Evaluation and we suggest using the regional framework described above as part of a biologically-based distribution procedure. Stock distribution is a science product and the MSAB's task is to develop TCEY distribution elements. However, where a science product fits into the management procedure is an element that could be evaluated in the MSE. Additionally, assumptions implicit in any of the procedures can be part of the uncertainty by introducing variability related to those assumptions. Elements of the TCEY distribution component may include the following.

- Use additional data, other than the fishery-independent data used to estimate stock distribution, to inform additional adjustments to the distribution of the TCEY to regions or IPHC Regulatory Areas within a Region.
- Assign a specific allocation when distributing the TCEY to IPHC Regulatory Areas within a Region.

MSE PROGRAM OF WORK FOR MSAB RELATED ACTIVITIES FOR 2018-2022

IPHC-2017-MSAB10-11 described a work plan consisting of seven tasks for the next five years. These tasks are described briefly below.

TASK 1: VERIFY THAT GOALS ARE STILL RELEVANT AND FURTHER DEFINE OBJECTIVES.

Relevant goals and measurable objectives are essential to the MSE process. They are necessary to determine what types of models are needed and how to evaluate the management strategies. Current goals and objectives defined by the MSAB are listed in Appendix A. This is an ongoing task since goals and objectives may change or expand over time.

TASK 2: DEVELOP PERFORMANCE METRICS TO EVALUATE OBJECTIVES

Measurable objectives guide the development of the simulation framework for a MSE, and performance metrics are needed to gauge the performance of a management strategy relative to those objectives. The outcome of this task is a list of performance metrics that would be informative to stakeholders, managers, and scientists to effectively evaluate the performance of different management strategies and the trade-offs between them. It is linked to the goals and objectives, thus is also an ongoing task.

TASK 3: IDENTIFY STRENGTHS AND WEAKNESSES OF SINGLE-AREA AND MULTI-AREA MODELS FROM A MSE PERSPECTIVE

The complexity of an operating model is an important factor to consider in a MSE. This task is to describe what is needed to develop single-area and multi-area operating models for use in closed-loop simulations, the resources needed to do so, and how much time it may take. Additionally, the strength and weaknesses of the coast-wide and multi-area operating models in relation to each measurable objective will also be presented. This task should be completed in early 2019.

TASK 4: IDENTIFY REALISTIC MANAGEMENT PROCEDURES OF INTEREST TO EVALUATE WITH A CLOSED-LOOP SIMULATION FRAMEWORK

The purpose of MSE is to evaluate management procedures by examining and comparing the performance and trade-offs of each. This task will be to identify realistic management procedures that are of interest to stakeholders, managers, and scientists, thus ensuring that the results of the MSE are pertinent and useful to managing the Pacific halibut stock. This is also an ongoing task, but outcomes are already being realized.

TASK 5: DESIGN A CLOSED-LOOP SIMULATION FRAMEWORK AND CODE A COMPUTER PROGRAM TO EXTEND THE PAST EQUILIBRIUM MODEL APPROACH

The majority of this document describes a framework for performing a MSE that extends on the past equilibrium model approach. Further work is needed to improve this framework (e.g., adding an estimation model) and a good design will ensure that the code is suitable to address current questions and flexible to accommodate future questions. Progress has been made on this task and the framework and code will continue to be developed in the future.

TASK 6: DEVELOP EDUCATIONAL TOOLS THAT WILL ENGAGE STAKEHOLDERS AND FACILITATE COMMUNICATION

For a stakeholder driven process to be effective, an understanding of the process and how to interpret results is necessary. These educational tools will facilitate communication and allow users to understand trade-offs between performance metrics given alternative management procedures. This is an ongoing task with collaboration between IPHC staff, stakeholders, and managers.

TASK 7: FURTHER THE DEVELOPMENT OF THE OPERATING MODELS

Currently, the operating model consists of coastwide models and cannot be used to evaluate area-specific objectives, which can only be answered with a multi-area model. Development of a multi-area model to evaluate area-specific objectives will occur over the next two years.

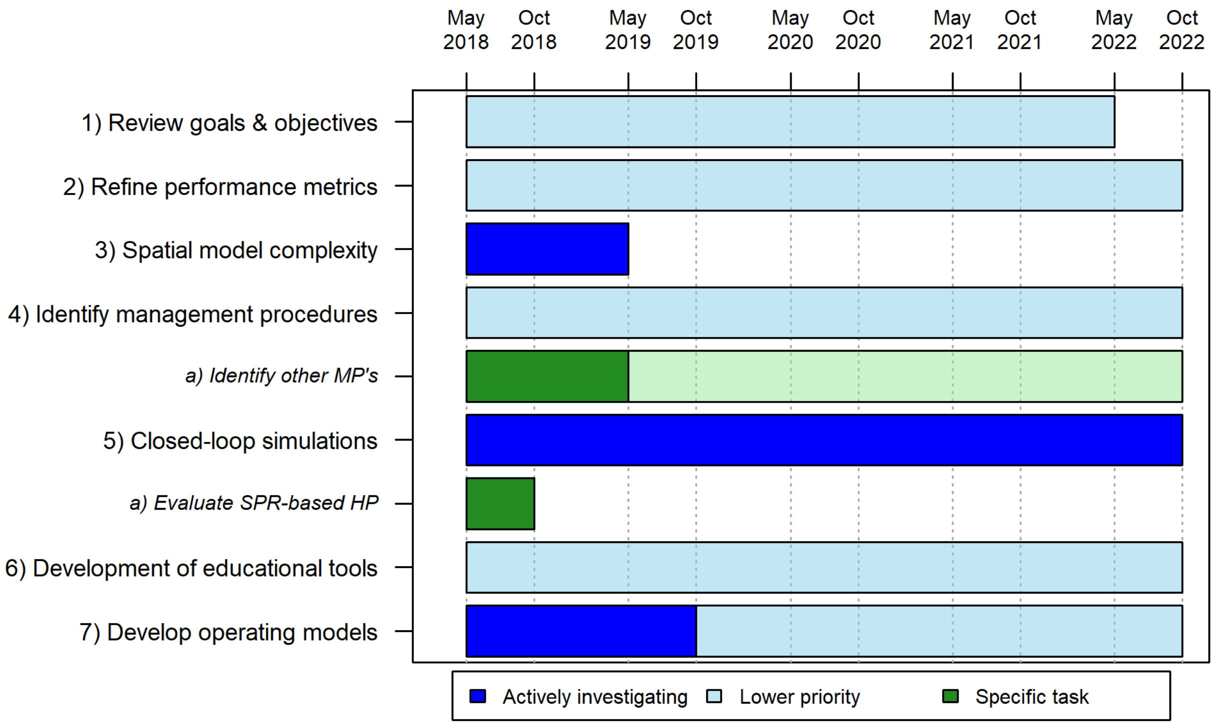

Figure 21: Gantt chart for the five-year work plan. Tasks are listed as rows. Dark blue indicates when the major portion of the main tasks work will be done. Light blue indicates when preliminary or continuing work on the main tasks will be done. Dark green indicates when the work on specific sub-topics will be done and light green shows when continuing work will be done. The end of the dark color shows when those results will be presented.

Discussions of this work plan with the MSAB resulted in the recommendation to prioritize the current work on evaluating the scale component of the harvest strategy policy to produce recommendations at AM095 in January 2019 (Table 6). After that it is expected that recommendations related to the TCEY distribution component (and updates to the scale component) will occur at AM097 in January 2021.

Table 6: MSAB recommended timeline of work and topics to present between 2018 and 2021. From IPHC-2017-MSAB10-R.

May 2018 Meeting
Review Goals
Look at results of SPR
Review Performance Metrics
Identify Scale MP's
Review Framework
Identify Preliminary Distribution MP's
October 2018 Meeting
Review Goals
Complete results of SPR
Review Performance Metrics
Identify Scale MP'S
Verify Framework
Identify Distribution MP's
Annual Meeting 2019
Recommendation on Scale Present possible distribution MP's
May 2019 Meeting
Review Goals
Spatial Model Complexity
Identify MP's (Distn Scale)
Review Framework
October 2019 Meeting
Review Goals
Spatial Model Complexity
Identify MP's (Distn Scale)
Review Framework
Review multi-area model development
Annual Meeting 2020
Update on progress
May 2020 Meeting
Review Goals
Review multi-area model
Review preliminary results
October 2020 Meeting
Review Goals
Review preliminary results
Annual Meeting 2021
Recommendations on Scale and Distribution

RECOMMENDATION/S

That the Commission:

1) **NOTE** paper IPHC-2017-IM093-10 which provided an update of MSE related activities in 2017, including a review of goals and objectives defined by the MSAB, an overview of the simulation framework to evaluate the fishing intensity and harvest control rules in the IPHC harvest strategy policy, results from the closed-loop simulations, ideas for distributing the TCEY to Regulatory Areas, and a five-year work plan.
2) **CONSIDER** the simulation framework and assumptions as described, including introducing variability to the Operating Model, simulating weight-at-age and an environmental regime, and allocation of the Total Mortality to sectors.
3) **CONSIDER** the long-term results looking at the outcomes of various management procedures and the trade-offs between them.
4) **RECOMMEND** management procedures (e.g. values of SPR in combination with a control rule threshold) that would meet the goal and objectives important to the Commission, based on the results shown, and additional procedures that may be of interest to evaluate in 2018.
5) **AGREE** whether the clear separation of stock distribution, and distribution procedures satisfies the Commission's recommendation to replace *apportionment* with a more suitable term.
6) **ENDORSE** the concept of distributing the TCEY to biological regions defined here as a method to satisfy the Commission's request to "*initiate a process to develop alternative, biologically based stock distribution strategies.*"

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APPENDIX A: GOALS, OBJECTIVES, AND PERFORMANCE METRICS

Table A1: Measurable objectives and associated performance metrics, as reported in the MSAB09 Report (IPHC-2017-MSAB09-R). Median operates on the independent simulations, while average refers to the average over a specific period of years in each simulation (e.g., the last 10 years). RSB refers to dynamic relative spawning biomass, a measure of stock status. Limit is the lower point of the control rule where fishing intensity is set to zero, and threshold is the upper point where fishing intensity begins to be adjusted downward. These are defined as values of RSB.

Biological Sustainability				
Measurable Objective	**Outcome**	**Time-frame**	**Probability**	**Performance Metrics**
Maintain a minimum of number of mature female halibut coast-wide	Number of mature female halibut less than a threshold	10 year period, long-term	0.01	Median average number of mature female halibut
Avoid very low stock sizes	RSB < Limit of control rule	10 year period, long-term	0.05	Probability that RSB is less than the limit
Mostly avoid low stock sizes	RSB < Threshold of control rule	10 year period, long-term	0.25	Probability that RSB is less than the threshold
When Limit < Estimated Biomass < Threshold, limit the probability of declines	SSB declines when Limit < RSB < Threshold	10 year period, long-term	0.05 – 0.5, depending on est. stock status	Probability that spawning biomass declines in the next year given that RSB is between the limit and threshold
Spawning Biomass	An absolute measure	10 year period, long-term	NA	Median average RSB

Minimize discard mortality				
Measurable Objective	**Outcome**	**Time-frame**	**Probability**	**Performance Metrics**
Discard mortality in the longline fishery	<10% of annual catch limit	10 year period, Long-term	0.25	Probability that discard mortality is greater than 10% of the directed fishery catch limit
Absolute	Discard mortality	10 year period, Long-term		Median average discard mortality

Fishery Sustainability, Stability, and Access				
Measurable Objective	**Outcome**	**Time-frame**	**Probability**	**Performance Metrics**
Maintain directed fishing opportunity	Fishery is open	Each year	0.05	Probability that the directed fishery catch limit is equal to zero
Maximize yield in each regulatory area		Each year	0.5	
Maintain median catch	Within ±10% of 1993-2012 average (72.3 M lbs)	Within 5 yrs, 10 yr per, long term		Probability that the directed fishery catch limit (FCEY) is greater than 79.5 M lbs and less than 65.1 M lbs
Maintain average catch	> 70% of historical 1993-2012 average	10 year period, long-term	0.1	Probability that the directed fishery catch limit is less than 50.6 M lbs
Limit annual changes in TAC, coast-wide and/or by Regulatory Area	Change in FCEY < 15%	10 year period, long-term		Probability that the change in directed fishery catch limit is more than 15%
Absolute	FCEY	10 year period, long-term	NA	Median average directed fishery catch limit
Absolute	Variability in FCEY	10 year period, long term		The average percent change in catch. Often called Average Annual Variability (AAV)

Minimize bycatch and bycatch mortality				
Measurable Objective	**Outcome**	**Time-frame**	**Probability**	**Performance Metrics**

Serve consumer needs				
Measurable Objective	**Outcome**	**Time-frame**	**Probability**	**Performance Metrics**

Preserve biocomplexity				
Measurable Objective	**Outcome**	**Time-frame**	**Probability**	**Performance Metrics**