An update of the IPHC Management Strategy Evaluation process for SRB016

PREPARED BY: IPHC SECRETARIAT (A. HICKS, P. CARPI, S. BERUKOFF, & I. STEWART; 10 JUNE 2020)

PURPOSE

To provide an update of International Pacific Halibut Commission (IPHC) Management Strategy Evaluation (MSE) activities including the definition and development of a framework to evaluate management procedures for distributing the TCEY.

1 INTRODUCTION

The Management Strategy Evaluation (MSE) at the International Pacific Halibut Commission (IPHC) has completed an initial phase of evaluating management procedures (MPs) relative to the coastwide scale of the Pacific halibut stock and fishery, and is developing a framework to additionally investigate MPs related to distributing the Total Constant Exploitation Yield (TCEY) to IPHC Regulatory Areas. The TCEY is the mortality limit composed of mortality from all sources except under-26-inch (66.0 cm, U26) non-directed commercial discard mortality, and is determined by the Commission at each Annual Meeting for each IPHC Regulatory Area (Figure 1).

The development of an MSE framework aims to support the scientific, forecast-driven study of the trade-offs between fisheries management scenarios. Crafting this tool requires

- the definition and specification of a multi-area operating model;
- an ability to condition model parameters using historical catch and survey data and other observations;
- identification and development of management procedures with closed-loop feedback into the operating model;
- definition and calculation of performance metrics and statistics based on defined objectives to evaluate the efficacy of applied management procedures.

Updates on the recent efforts in these areas are outlined below.

2 FRAMEWORK ELEMENTS

The MSE framework includes elements that simulate the Pacific halibut population and fishery (Operating Model, OM) and management procedures with a closed-loop feedback (Figure 2). Specifications of some elements are described below, with additional technical details in document IPHC-2020-SRB016-INF01.

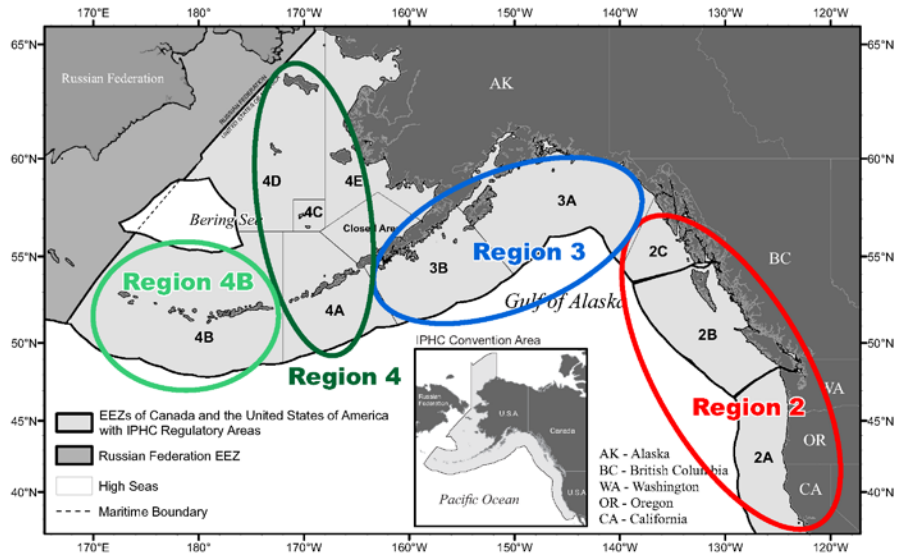

Figure 1: Biological Regions overlaid on IPHC Regulatory Areas. Region 2 comprises 2A, 2B, and 2C, Region 3 comprises 3A and 3B, Region 4 comprises 4A and 4CDE, and Region 4B comprises solely 4B.

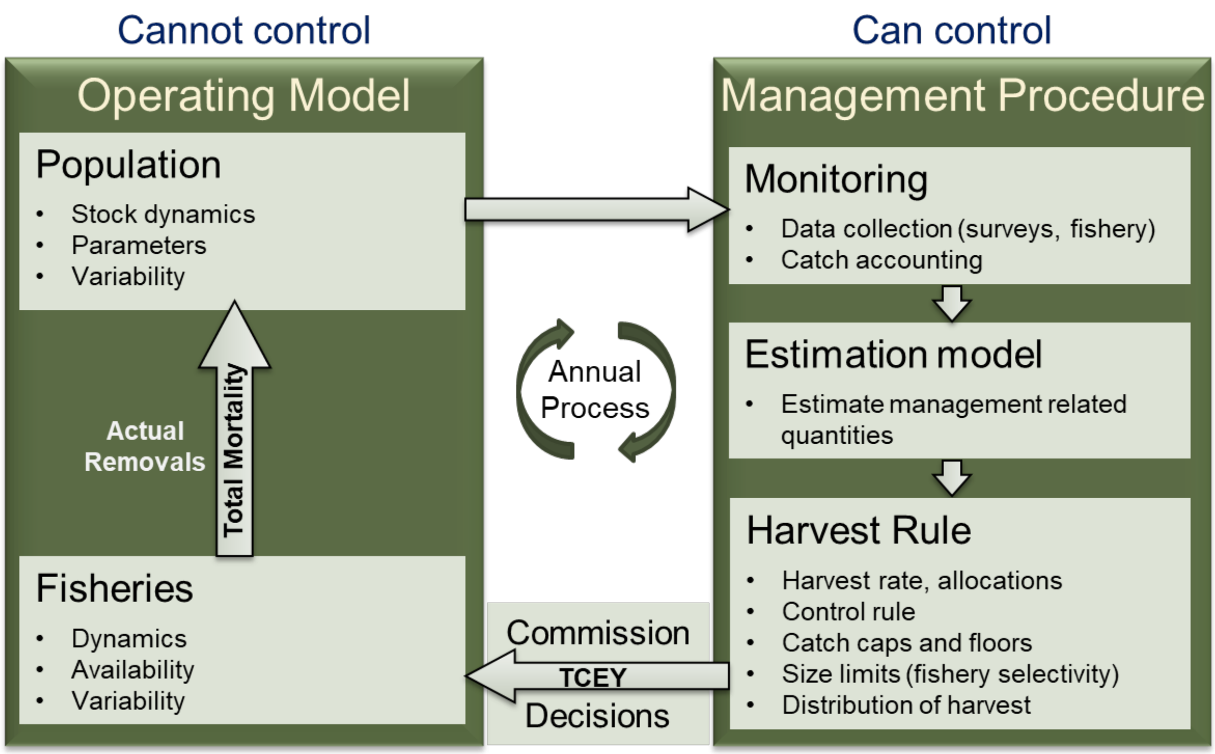

Figure 2: Illustration of the closed-loop simulation framework with the operating model (OM) and the Management Procedure (MP). This is the annual process on a yearly timescale.

2.1 Multi-area operating model

The generalized operating model is able to model multiple spatial components, which is necessary because mortality limits are set at the IPHC Regulatory Area level (Figure 1) and some objectives are defined at that level. Written in the programming language C++ with JavaScript Object Notation (JSON) input files, the OM is flexible, fast, modular, and easily adapted to many different assumptions. The operating model is a simulation tool and uses external optimisation tools for estimation of parameters. It will be a very useful tool for many investigations of the Pacific halibut fishery in the future.

The technical details of the multi-area operating model, which continues to be under development, are supplied in document IPHC-2020-SRB016-INF01. Some background information on specific components and the incorporation of uncertainty is supplied below.

2.1.1 General process of running the operating model

The use of multiple input JSON-formatted files allows for the simulation of many configurations of the Pacific halibut population and associated fisheries. Any number of areas/regions can be specified along with any number of fisheries that operate in those areas at a specified time in the year. Various parameters, such as natural mortality, movement probabilities, selectivity, etc., are inputs and most can vary over time, region, sex, fishery, and age where relevant.

The OM begins by calculating the unfished equilibrium population given an input set of biological parameters. It then simulates the annual process during what is called an “initial period” with a fixed mortality level for each fleet (i.e., catch + discard mortality). This initial period allows for the stock to distribute across modelled areas to an equilibrium state given recruitment deviations and fishing mortality. During a subsequent “main period”, the population and dynamics are simulated using input annual fishing mortality, time-varying parameters such as selectivity, recruitment variability, and annual movement between areas. The parameterized model that is run through the main period is called the conditioned model. It is at the end of this main period that closed-loop simulations, called the “projection period,” begin.

The projection period can occur in four different ways:

1. A script written for the R statistical language (R Core Team 2020) containing all of the details of the management procedure being evaluated is called by the OM at the beginning of the year to determine the total mortality (TM) for each fishery. The TMs are read back into the OM along with other projected annual processes (e.g., weight-at-age as described below) to simulate the fish population one year forward.
2. A script written for the R statistical language calls the OM which reads in a saved state from disk using TileDB[1], containing the stock state at the start of the projection period as a result of development from the initial period to the end of the main period. After projecting the fish population and fisheries one year forward, the state is written back to disk and the R script performs external calculations such as the management procedure to determine total mortality.

[1] https://tiledb.com/

3. The OM is self-sufficient and performs “no estimation error” closed-loop simulations using the spawning potential ratio (SPR) and simple procedures to determine the TM for each fishery.
4. The framework including the OM and management procedures are part of one executable with OM and MP specifications defined through JSON input files.

The first method, where the OM calls an R script containing the details of the management procedure, is currently used, and the other three methods are under development.

2.1.2 Population and fishery spatial specification

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). The structure of two of the four current Pacific halibut stock assessment models was developed around identifying portions of the data (fishery-independent and fishery-dependent data) that correspond to differing biological and population processes within the larger Pacific halibut stock. This approach, referred to as ‘areas-as-fleets’ is commonly used in stock assessments (Waterhouse et al. 2014), and was the approach recommended for inclusion in the ensemble developed in 2014 during the SRB review of models and used in all assessments since (Cox et al. 2016, Stewart & Martell 2015, 2016). The approach introduced the concept of Biological Regions.

Biological Regions (Figure 1) were defined with boundaries that matched some of the IPHC Regulatory Area boundaries for the following reasons. First, data for stock assessment and other analyses are most often reported at the IPHC Regulatory Area scale and are largely unavailable for sub-Regulatory Area evaluation. Particularly for historical sources, there is little information to partition data to a portion of a Regulatory Area. Second, it is necessary to distribute TCEY to IPHC Regulatory Areas for quota management. If a Region is not defined by boundaries of IPHC Regulatory Areas (i.e. a single IPHC Regulatory Area is in multiple Regions) it will be difficult to create a distribution procedure that accounts for biological stock distribution and distribution of the TCEY to Regulatory Areas for management purposes. Further, the structure of the current directed fisheries does not delineate fishing zones inside individual IPHC Regulatory Areas, so there would be no way to introduce management at that spatial resolution.

To a certain degree, Pacific halibut within the same Biological Region share common biological traits different from adjacent Biological Regions. These traits include sex ratios, age composition, and size-at-age, and historical trends in these data may be indicative of biological diversity within the greater Pacific halibut population. Furthermore, tagging studies have indicated that within a year, larger Pacific halibut tend to undertake feeding and spawning migrations within a Biological Region, and movement between Biological Regions typically occurs between years (Loher and Seitz 2006; Seitz et al. 2007; Webster et al. 2013).

Given the goals to divide the Pacific halibut stock into somewhat biologically distinct regions and preserve biocomplexity across the entire range of the Pacific halibut stock, Biological Regions are considered by the IPHC Secretariat, and supported by the SRB (paragraph 31 IPHC-2018-

SRB012-R), to be the best option for biologically-based areas to meet management needs. They also offer a parsimonious spatial separation for modeling inter-annual population dynamics.

However, as mentioned earlier, mortality limits are set for IPHC Regulatory Areas and thus directed fisheries operate at that spatial scale. Furthermore, since some fishery objectives have been defined at the IPHC Regulatory Area level, the TCEY will need to be distributed to that scale. Even though the population is modelled at the Biological Region scale, fisheries can be modelled at the IPHC Regulatory Area scale by using an areas-as-fleets approach within Biological Regions. This requires modelling each fleet with separate selectivity and harvest rates that operate on the biomass occurring in the entire Biological Region in each year. The following is a discussion of the pros and cons of this method.

First, modelling the population dynamics at the IPHC Regulatory Area scale would require intra-annual dynamics to be modelled, dividing the year into seasons to model movement between IPHC Regulatory Areas. There is evidence that such intra-annual movements occur (Loher and Seitz, 2006) and fisheries in adjacent IPHC Regulatory Areas may intercept the same pool of fish (Loher 2011). Using Biological Regions assumes that all fisheries within a Region have access to the pool of Pacific halibut in that Region in that year. This greatly simplifies the calculations and eliminates the need to parameterize intra-annual movement.

Additionally, calculating statistics specific to IPHC Regulatory Areas requires assumptions about mechanisms determining future distribution of biomass within each Biological Region. For example, simulating the observed proportion of biomass in each IPHC Regulatory Area (e.g., to mimic the current interim management procedure) requires simulating a survey biomass for each IPHC Regulatory Area. Likewise, determining some performance metrics related to IPHC Regulatory Area objectives may be difficult to calculate (such as the proportion of O26 fish in each IPHC Regulatory Area). The distribution of the population within a Biological Region is currently approximated assuming specified proportions of the population in each IPHC Regulatory Area within a Biological Region that are based on historical observations. These proportions are constant over ages and allows for the calculation of statistics specific to IPHC Regulatory Areas. Future improvements to the framework will allow for different options such as modelling proportions based on population attributes and accounting for year to year variability.

Fisheries were defined by IPHC Regulatory Areas (or combinations of areas if fishing mortality in that area was small) and in five general categories or sectors consistent with the definitions in the recent IPHC stock assessment (IPHC-2020-AM096-09 Rev_2):

- **directed commercial** representing the O32 mortality from the directed commercial fisheries including O32 discard mortality;
- **directed commercial discard** representing the U32 discard mortality from the directed commercial fisheries, comprised of Pacific halibut that die on lost or abandoned fishing gear, and Pacific halibut discarded for regulatory compliance reasons;
- **non-directed commercial discard mortality** 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.

Table 1 shows the summed mortality for each of these sectors by IPHC Regulatory Area or Biological Region. Thirty-three (33) fisheries were defined as a sector/area combination based on the amount of mortality in the combination, data availability, and MSAB recommendations (Table 2).

Table 1: Summed mortality (millions of net pounds) from 1992 through 2019 by fisheries and IPHC Regulatory Area or Biological Region.

Year	2A	2B	2C	3A	3B	4A	4CDE	4B
Directed commercial	17.5	259.8	205.5	551.2	252.4	78.2	72.5	62.8
Directed commercial discard mortality	0.5	7.1	5.2	16.7	10.7	2.1	1.3	0.8
Non-directed commercial discard mortality	11.8	12.0	4.5	73.6	36.2	39.2	16.2	128.6
Recreational	13.7	31.8	71.1	152.2	0.5	1.4	<0.1	<0.1
Subsistence	0.7	9.6	10.3	7.6	1.0	0.6	<0.1	2.4

The Fishery-Independent Setline Survey (FISS) is included as a fishery with no mortality to output summaries of observations such as indices and observed proportions-at-age in the population available to the survey at a specific time and in a specific region. Mortality from the FISS is included with the directed commercial fishery mortality, although it could be kept separate.

2.1.3 Fishery and survey selectivity and retention

Selectivity and retention determine the age composition of fishery mortality and ensure the removal of appropriate numbers-at-age from the population when mortality occurs in the annual time-step. Selectivity represents the proportion at each age that is captured by the gear. Retention represents the proportions-at-age that are retained and landed if caught (i.e., 1 - retention is the proportion-at-age that is released). The product of selectivity and retention is called the “keep curve” and represents the proportions-at-age from the population that are landed. Some fish that are not retained may survive; thus, a discard mortality rate is used to indicate the proportion of fish that are not retained and die after release.

Table 2: The thirty-three fisheries in the OM, the IPHC Regulatory Areas they are composed of, and the 2019 mortality (millions of net pounds) for each.

Fishery	IPHC Regulatory Areas	2019 Mortality
Directed Commercial2A	2A	0.89
Directed Commercial 2B	2B	5.22
Directed Commercial 2C	2C	3.67
Directed Commercial 3A	3A	8.16
Directed Commercial 3B	3B	2.31
Directed Commercial 4A	4A	1.45
Directed Commercial 4B*	4B	1.00
Directed Commercial 4CDE	4CDE	1.65
Directed Commercial Discards 2A	2A	0.03
Directed Commercial Discards 2B	2B	0.13
Directed Commercial Discards 2C	2C	0.06
Directed Commercial Discards 3A	3A	0.32
Directed Commercial Discards 3B	3B	0.15
Directed Commercial Discards 4A	4A	0.09
Directed Commercial Discards 4B	4B	0.03
Directed Commercial Discards 4CDE	4CDE	0.07
Non-directed Commercial Discards 2A	2A	0.13
Non-directed Commercial Discards 2B	2B	0.24
Non-directed Commercial Discards 2C	2C	0.09
Non-directed Commercial Discards 3A	3A	1.65
Non-directed Commercial Discards 3B	3B	0.48
Non-directed Commercial Discards 4A	4A	0.35
Non-directed Commercial Discards 4CDE	4CDE	3.50
Non-directed Commercial Discards 4B	4B	0.15
Recreational 2B	2B	0.86
Recreational 2C	2C	1.89
Recreational 3A	3A	3.69
Subsistence 2B	2B	0.41
Subsistence 2C	2C	0.37
Subsistence 3A	3A	0.19
Recreational/Subsistence 2A	2A	0.48
Recreational/Subsistence 3B	3B	0.02
Recreational/Subsistence 4	4A, 4CDE	0.06

*The small amount of recreational and subsistence mortality from IPHC Regulatory Area 4B is included in Directed Commercial 4B

Retention is not modelled specifically at this time because directed commercial discard mortality is modelled as a separate sector, and discard mortality for other sectors is included in the total mortality for those sectors. Initial parameters for selectivity when conditioning models were determined from the estimated parameters in the recent stock assessment (IPHC-2020-SA-01) including annual deviations in selectivity for the directed fisheries and the survey. These parameters were modified as necessary to improve fits to data and to reflect differences in implied availability of a spatially explicit model compared to the coastwide stock assessment.

2.1.4 Weight-at-age

Empirical weights-at-age by region for the population, fisheries, and survey are determined using observations from the FISS and the fisheries, as is done with the stock assessment models (IPHC-2020-SA-02) and as described in detail in Stewart and Martell (2016). Smoothed observations of weight-at-age from NMFS trawl surveys were used to augment weights-at-age for ages 1-6 in the fishery sectors and survey. Population weight-at-age is smoothed across years to reduce observation error. Finally, survey and population weight-at-age prior to 1997 is scaled to fishery data because survey observations are limited if present at all.

2.1.5 Movement

Many data sources are available to inform Pacific halibut movement. Decades of tagging studies and observations have shown that important migrations characterize both the juvenile and adult stages and apply across all regulatory areas. The conceptual model of halibut ontogenetic and seasonal migration, including main spawning and nursery grounds, as per the most current knowledge, was presented in IPHC-2019-MSAB014-08 and was used to assist in parameterizing movement rates in the OM.

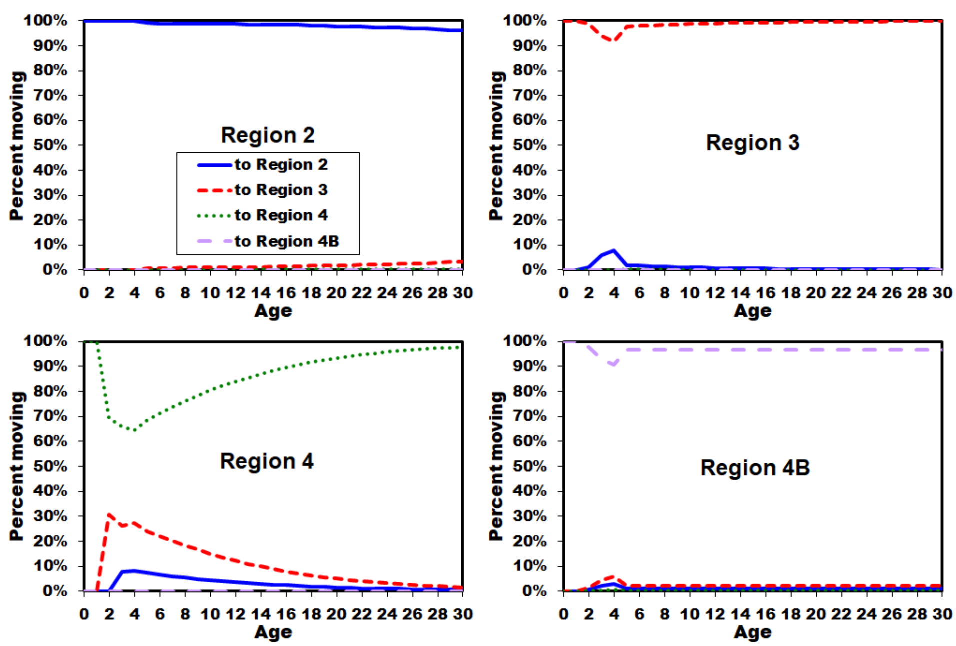

Figure 3: Estimated aggregate annual movement rates by age from Biological Regions (panels) based on currently available data (from IPHC-2019-AM095-08).

In 2015, the many sources of information were assembled into a single framework representing the IPHC's best available information regarding movement-at-age among Biological Regions. Key assumptions in constructing this hypothesis included:

- ages 0-1 do not move (most of the young Pacific halibut reported in Hilborn et al. (1995) were aged 2-4),
- movement generally increases from ages 2-4,
- age-2 Pacific halibut cannot move from Region 4 to Region 2 in a single year, and
- relative movement rates of Pacific halibut of age 2-4 to/from Region 4 are similar to those observed for 2-4-year-old Pacific halibut in Region 3, relative to older Pacific halibut.

Based on these assumptions, appreciable emigration is estimated to occur from Region 4, decreasing with age. Pacific halibut age-2 to age-4 move from Region 3 to Region 2 and from Region 4B to Regions 3 and 2, and some movement of older Pacific halibut is estimated to occur from Region 2 back to Region 3 (Figure 3).

The conceptual model and assembled movement rates were used to inform the development of the MSE operating model framework and are being used as a starting point to incorporate variability and alternative movement hypotheses in Pacific halibut movement dynamics. Movement in the OM is modelled using a transition matrix as the proportion of individuals that move from one Biological Region to another for each age class in each year.

The transition matrix with movement probabilities from one region to another (including staying in the region of origin) can either be entered directly or parameterized using several functional forms. Current functional forms include *constant*, *exponential*, and *double exponential*, as shown in equations 1-4, and can closely mimic the movement probabilities described in IPHC-2019-AM095-08 that are based on data, and shown along with fits in Figure 4: Estimates of movement rates by age from data (black solid circles) and fits (green circles) to those estimates using various functional forms described in Equations 1-4..

Constant
$$\omega_{a|j\to k} = \begin{cases} 0 & a \le lastAge0 \\ c & a > lastAge0 \end{cases} \quad (1)$$

Exponential
$$\omega_{a|j\to k} = \begin{cases} 0 & a \le lastAge0 \\ \dfrac{e^{\lambda(a-lastAge0+1)}}{\max(\omega_{a|j\to k})} \times (\gamma_2 - \gamma_1) & a > lastAge0 \end{cases} \quad (2)$$

Double-exponential
$$\omega_{a|j\to k} = \begin{cases} 0 & a \le lastAge0 \\ \dfrac{e^{\lambda(a-lastAge0)} - 1}{\max(\omega_{a|j\to k})} \times \gamma_2 & lastAge0 < a < peak \\ (\gamma_2 - \alpha)e^{-\lambda(a-lastAge0+1)} + \alpha & a > peak \end{cases} \quad (3)$$

Values
$$\omega_{a|j\to k} = \begin{cases} v_a & a \le lastAge \\ v_{lastAge} & a > lastAge \end{cases} \quad (4)$$

where $lastAge0$ is the oldest age with a movement probability of zero before the first non-zero movement probability, α is the asymptote, γ_1 is the minimum probability in that range of ages, and γ_2 is the maximum probability in that range of ages. These parameters are used to scale the relationship to the appropriate range and λ determines the rate of increase or decrease.

These parameterizations overcome an impediment identified in the development of the spatially explicit stock assessment model using stock synthesis and presented at SRB009. The functional forms allow for efficient and easy modifications to input files to depart from the estimated movement rates based on data, which occurs when conditioning the models. This is useful because there are many assumptions in the estimates, especially for young ages, and the OM will need to include uncertainty as well as possibly time-varying aspects.

2.1.6 Maturity

Spawning biomass for Pacific halibut is currently calculated from weight-at-age and a maturity-at-age ogive that is assumed to be constant over years. There is currently no evidence (IPHC-2020-SA-02) for skip spawning or maternal effects (increased reproductive output or offspring survival for larger/older females) and thus they are not modelled, but could be added. Stewart & Hicks (2017) examined the sensitivity of the estimated biomass to a trend in declining spawning potential (caused by a shift in maturity or increased skip spawning) and found that under that condition there was a bias in both scale and trend of recent estimated spawning biomass. The current SRB document IPHC-2020-SRB016-07 tested maternal effects on estimates of recruitment and concluded “there appears to be no evidence in the current data that the addition of a simple age-based maternal effects relationship improves the ability of the current stock assessment models to explain the time-series of estimated recruitments.” Ongoing research on maturity and skip spawning will help to inform future implementations of the basis for and variability in the determination of spawning output.

2.1.7 Uncertainty and variability in the operating model

Uncertainty and variability are important to consider, as the goal of an MSE is to develop management procedures that are robust to both. The OM should simulate potential states of the population in the future, uncertainties within the management procedure, and variability when implementing the management procedure.

2.1.7.1 Uncertainty in the conditioned OM

The conditioned OM is a representation of the Pacific halibut population and matches observations from the fishery, survey, and research. Uncertainty in these observations are included in the OM by varying parameters in two different ways. First, parameters vary between simulated trajectories and are drawn from correlated probability distributions that are derived from estimation procedures (e.g., the stock assessment). Second, specific parameters are fixed at different values representing potential states. Trajectories are simulated using both methods and then integrated appropriately to produce distributions of potential outcomes.

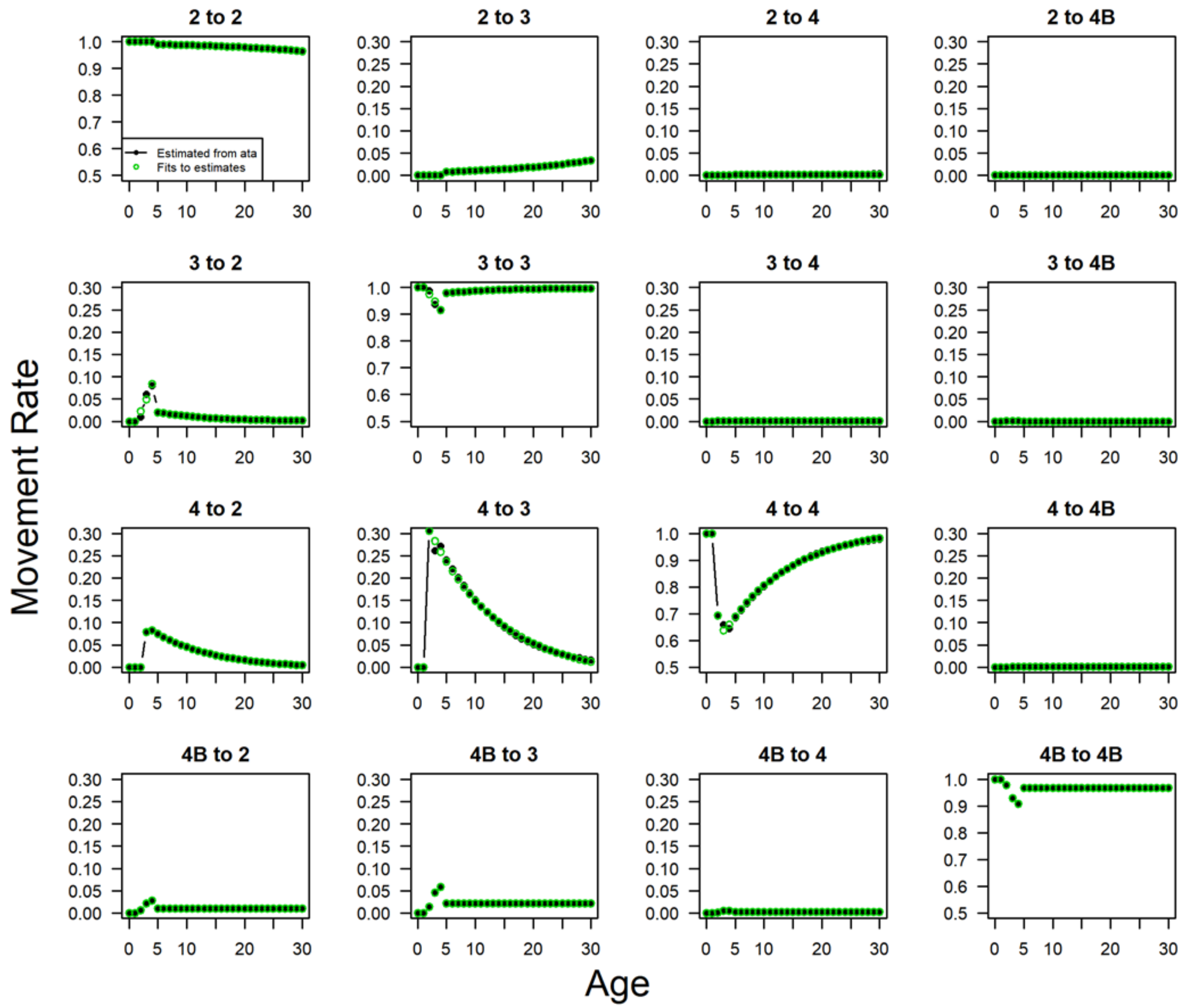

Figure 4: Estimates of movement rates by age from data (black solid circles) and fits (green circles) to those estimates using various functional forms described in Equations 1-4.

Table 3: Major sources of parameter uncertainty and variability in the conditioned operating model (OM).

Process	Uncertainty
Natural Mortality (*M*)	Estimated from assessment
Steepness	Estimated or fixed at specific values
Recruitment	Random lognormal deviations, distributed to Biological Regions
Size-at-age	Annual weight-at-age by Biological Region fixed for each year
Average recruitment	Estimated by the effect of the coastwide environmental regime shift
Selectivity	Estimated selectivity parameters; time-varying for some fisheries
Movement	To be determined

2.1.7.2 Projected population variability

Variability in the projected population is a result of initializing the population with a range of parameters to recreate a range of historical trajectories and including additional variability in certain population processes in the projection. The major sources of variability in the projections are shown in Table 4 and some are described in more detail below.

Table 4: Major sources of projected variability in the operating model (OM).

Process	Variability
Recruitment	Random, lognormal deviations, distributed to Biological Regions with deviations
Regime Shifts	Autocorrelated indicator based on properties of the PDO to adjust average recruitment
Size-at-age	Annual and cohort deviations in weight-at-age by Biological Region, with approximate historical bounds
Sector mortality	Sector mortality allocation variability within an area
Selectivity	Time-varying deviations of directed fishery selectivity
Implementation	Three potential sources of implementation variability: decisions, annual realizations, and catch estimation uncertainty.
Movement	Annual or regime-specific deviations in parameters

2.1.7.3 Linkage between average coastwide recruitment and environmental conditions

The average recruitment (R_0) is related to the Pacific Decadal Oscillation index[2], expressed as a positive or negative regime (IPHC-2020-SA-02). R_0 is multiplied by $e^{I\delta}$, where I is an indicator of the negative (0) or positive (1) regime, and δ is a parameter determining the magnitude of that multiplier. The parameter δ, and uncertainty, was determined from the stock assessment.

The regime was simulated in the MSE by generating a 0 or 1 to indicate the regime of each future year, as described in IPHC-2018-MSAB011-08. To encourage regimes between 15 and 30 years in length (assuming a common periodicity, although recent years have suggested less), the environmental index was simulated as a semi-Markov process, where each subsequent year depends on recent years. However, the probability of changing to the opposite regime was a function of the length of the current regime, with a change probability equal to 0.5 at 30 years, and a probability near 1 at 40 or greater years. This default parameterization results in simulated

[2] https://oceanview.pfeg.noaa.gov/erddap/tabledap/cciea_OC_PDO.htmlTable?time,PDO

regime lengths most often between 20 and 30 years, with occasional runs between 5 and 20 years or greater than 30 years. However, this can be modified to test other scenarios.

2.1.7.4 Projected weight-at-age

Weight-at-age varies over time historically, and the projections capture that variation using a random walk from the previous year. 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 was implemented using the same ideas as in the coastwide MSE (IPHC-2018-MSAB011-08), but was modified to incorporate autocorrelation in a more straightforward manner, and allow for slight departures between regions and fisheries.

The method used to simulate weight-at-age was as follows.

1. A single deviate (d_1) was generated from a normal distribution with a standard deviation determined from a 5% coefficient of variation and the mean of the weight-at-age from 1935 to 2019.
2. A deviate for each age 6 and greater, sex, region, and fishery ($d_{2,a,s,r,f}$) is generated from a normal distribution with a standard deviation determined from a 1% coefficient of variation and the mean of the weight-at-age from 1935 to 2019.
3. The projected weight-at-age for a region/fishery is from an ARIMA process with deviates d_1 and $d_{2,a,s,r,f}$ applied

   $$w_{a,s,r,f} = w_{a-1,s,r,f} + 0.45\left(w_{a-1,s,r,f} - w_{a-2,s,r,f}\right) + 0.30\left(w_{a-1,s,r,f} - w_{a-2,s,r,f}\right) + d_1 + d_{2,a,s,r,f}$$

   where 0.45 and 0.30 were determined by fitting an ARIMA(2,1,0) model to past observations of weight-at-age. The cv's for d_1 and d_2 were determined from past variability and *ad hoc* matching of simulated projection outputs to past variability.
4. Projected weight-at-age was maintained within bounds determined by extending the observed range of historical weight-at-age by 5%. If a weight at a specific age exceeded the bound, the deviation for that weight-at-age was reduced such that it was at the bound.

The overall deviate d_1 above is the main driver of weight-at-age and captures the past observations of variability in weight-at-age over time. An example projection is shown in Figure 5: Past observed (shaded area) and two examples of possible one-hundred-year projections of weight at ages 5, 8, 12, 15, 20, and 25..

2.1.7.5 Time-varying selectivity

Time-varying selectivity is estimated in the stock assessment for only the directed fishery in historical years in order to allow for spatial availability and changes in weight-at-age in these coastwide models. The coastwide MSE followed a similar approach by linking changes in selectivity to weight-at-age. Changes in selectivity may be related to changes in weight-at-age because weight-at-age is a proxy for changes in size. Change in spatial availability is also a factor in time-varying coastwide selectivity, and the multi-area OM may alleviate some of that variability.

A similar approach is used when projecting in the multi-area OM, and the details are still being developed.

2.1.7.6 Implementation variability

Implementation variability consists of three components. The first is the departure from the management procedure during the decision-making process. For example, the MP may result in a total mortality of 40 Mlbs, but the decision may be to implement a total mortality of 36 Mlbs for various economic and social reasons. The second component of implementation variability is the fact that the fisheries do not achieve the mortality limits exactly. In recent years, the actual total fishery mortality has been slightly less than mortality limits, although some sectors have exceeded the limits. These two components of implementation variability are modelled in the OM, although the details are still being determined.

An additional source of variability associated with mortality from fishing is the uncertainty in the estimated amount of mortality. This is important for the application of the management procedure, for example in the estimation models. This uncertainty is not currently incorporated but may be for future simulations.

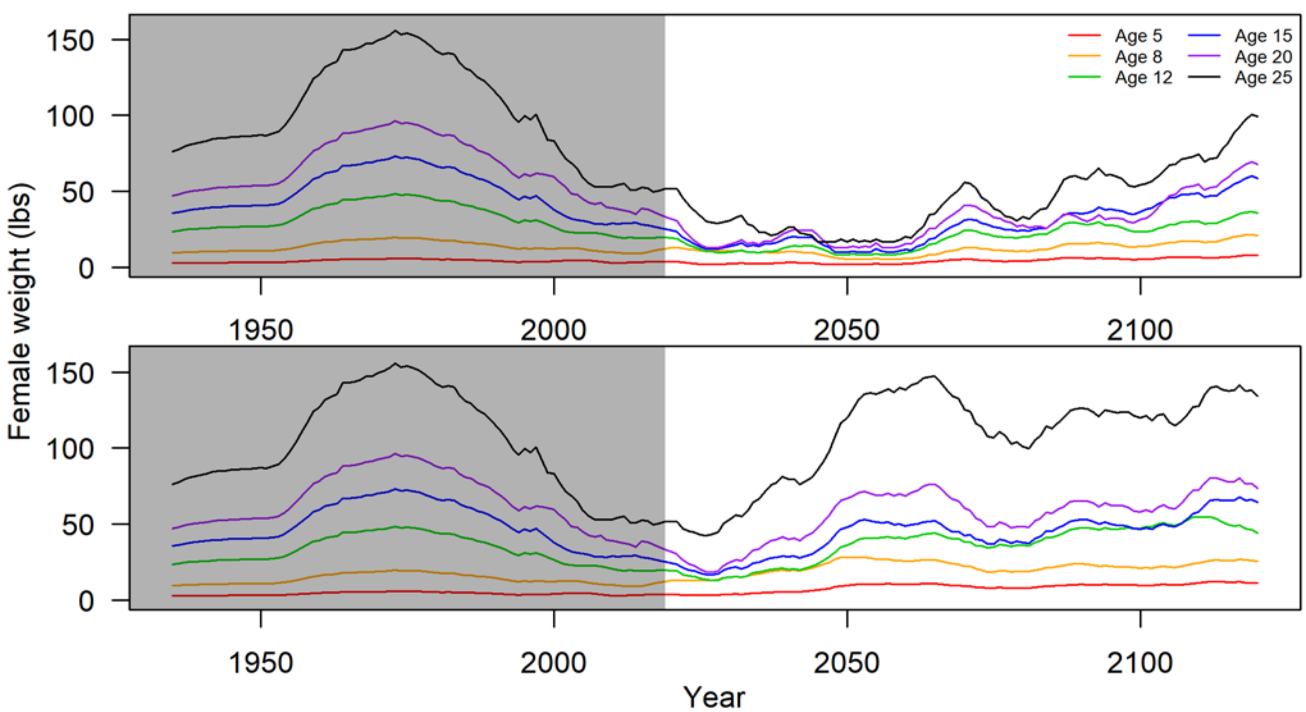

Figure 5: Past observed (shaded area) and two examples of possible one-hundred-year projections of weight at ages 5, 8, 12, 15, 20, and 25.

2.2 Management Procedures for coastwide scale and distribution of the TCEY

The management procedure consists of three elements (Figure 2). Monitoring (data generation) is the code that simulates the data from the operating model that are used by the estimation model. It simulates the sampling process and can introduce variability, bias, and any other properties that are desired. The Estimation Model (EM) is analogous to the stock assessment and includes estimation error in the simulation. 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. Simplification of the full stock assessment ensemble was necessary to keep simulation times within reason. The harvest rule is the application of the estimation model output along with the scale and distribution management procedures (Figure 2) to produce the mortality limit for that year. The details of the management procedures are in development and concepts described in IPHC-2020-MSAB015-07 are being considered.

The 96th Session of the IPHC Annual Meeting (AM096) discussed the recommendations from the MSAB and the IPHC Secretariat on the coastwide results of the MSE and agreed to hold an inter-sessional meeting soon after AM096 to provide further direction. At the 96th Annual Meeting the Commission noted the recommendation from the MSAB after evaluating the coastwide MSE that the following harvest rule components meet the coastwide objectives (IPHC-2020-AM096-R, para 79, point 5):

a) SPR values greater than 40%;*

b) A control rule of 30:20;

c) Constraints on the annual change in the TCEY that either limit the annual change to 15%, use a slow-up, fast-down approach, or fix the mortality limits for three-year periods, recognizing that additional types of constraints may also meet the objectives.

*SPR values in the range between 40 to 46% meet the objectives, as noted in para 52 of https://www.iphc.int/uploads/pdf/msab/msab13/iphc-2019-msab013-r.pdf.

At the 6th Special Session of the Commission, two specific recommendations were made on the MSE (IPHC-2020-CR-007):

***IPHC-2020-ID001:** The Commission **RECOMMENDED** that the primary coastwide and area-specific objectives outlined in Table 1 of Appendix A be used for evaluating MSE results conditional on future consideration of the objectives after preliminary MSE results are presented at MSAB015 in May 2020.*

***IPHC-2020-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, noting the additional components intended to apply for a period of 2020 to 2022 as defined in IPHC-2020-AM096-R paragraphs 97 b, c, d, and e. Specifically, these additional components are allocations to 2A and 2B, accounting for some impacts of U26 non-directed discard mortality, and the use of a rolling three-year average for projecting non-directed fishery discard mortality.*

These two recommendations endorse the coastwide and area-specific objectives defined at MSAB014, and the revision of the reference Spawning Potential Ratio (SPR, or fishing intensity) from 46% to 43% based on the analysis presented to SRB015 and MSAB014.

2.2.1 General procedure for distributing the TCEY

The general procedure for distributing the TCEY begins with the coastwide TCEY determined from the stock assessment and fishing intensity defined by the reference SPR. The TCEY can be distributed to Biological Regions first and then to IPHC Regulatory Areas, or directly to IPHC Regulatory Areas; however, maintaining spawning biomass in each Biological Region is a primary objective. Relative adjustments can be applied in each step of the distribution process. Typically, the distribution procedure does not appreciably alter the coastwide fishing intensity (although a slight change may occur due to different selectivity patterns accessing the population), however there is interest in management procedures that are only limited to being less than a maximum fishing intensity (i.e., above a minimum SPR).

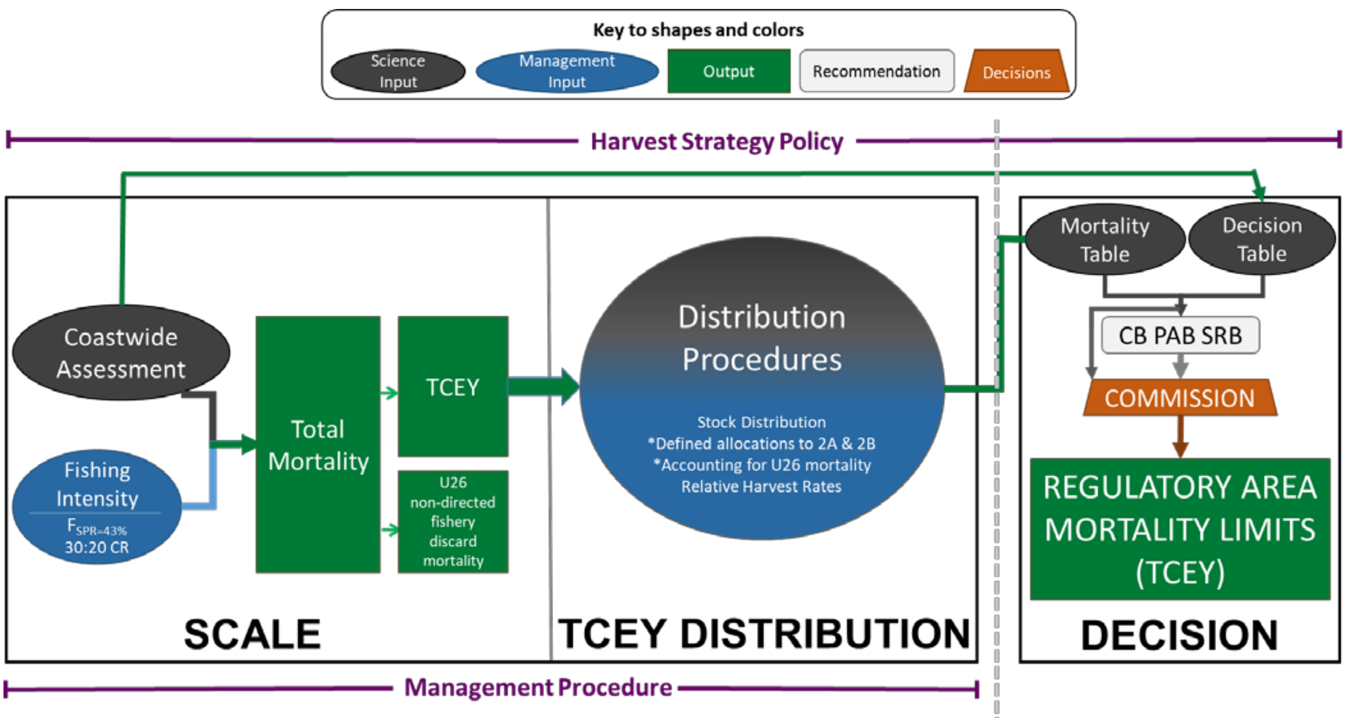

Figure 6: Illustration of the Commission interim IPHC harvest strategy policy (reflecting paragraph ID002 in IPHC CIRCULAR 2020-007) showing the coastwide scale and TCEY distribution components that comprise the management procedure. Items with an asterisk are three-year interim agreements to 2022. The decision component is the Commission decision-making procedure, which considers inputs from many sources.

The general procedure is described below. Only steps 1 and 3 are required while steps 2 and 4 are optional.

1. **Coastwide scale (*required*)**
    1.1. **Estimation model (science-based, *required*)**: A statistical analysis or summary of data to inform the current status of the stock and possibly projections given various mortality limits. This may be as complex as a stock assessment or as straightforward as the estimate of relative coastwide abundance/biomass from the modelled survey index.
    1.2. **Procedural fishing intensity (management-derived, *required for an assessment-based approach*):** Determine the coastwide total mortality using a procedural SPR that is most consistent with IPHC coastwide objectives defined by the Commission, removing the U26 non-directed fishing discard mortality from the Total Mortality to determine the coastwide TCEY.
    1.3. **Additional coastwide adjustments:** Apply additional adjustments to the procedural SPR (i.e., fishing intensity) or TCEY at the coastwide level. The procedural SPR may be modified based on stock status (e.g., a 30:20 control rule). Additionally, constraints on the annual change in TCEY may be applied.
2. **Regional distribution (*optional*)**
    2.1. **Regional Stock Distribution (science-based, *required when using the Regional step*):** Distribute the coastwide TCEY to four (4) biologically-based Regions (Figure 1) using the proportion of the stock estimated in each Biological Region from the modelled FISS estimates. “All sizes” WPUE is the most congruent metric to distribute the TCEY at this scale.
    2.2. **Regional Relative Fishing Intensity (science-based, *optional*):** Adjust the distribution of the TCEY among Biological Regions to account for migration, productivity, and other biological characteristics of the Pacific halibut observed in each Biological Region.
    2.3. **Regional Allocation Adjustment (management derived, *optional*):** Adjust the distribution of the TCEY among Biological Regions to account for other factors. This may include evaluation of recent trends in estimated quantities (such as fishery-independent WPUE), inspection of historical trends in fishing intensity, recent or historical fishery performance, and uncertainty. Regional relative harvest rates may also be determined through negotiation, leading to an allocation agreement for further regional adjustment of the TCEY.
3. **IPHC Regulatory Area Allocation (*required with at least one sub-option*)**
    3.1. **IPHC Regulatory Area Stock Distribution (science-based):** Distribute the coastwide (if step 2 is omitted) or regional TCEY to IPHC Regulatory Areas using the proportion of the stock estimated in each IPHC Regulatory Area from the modelled FISS estimates. “All sizes” WPUE is the most congruent metric to distribute the TCEY at this scale.

3.2. **IPHC Regulatory Area Allocation (management derived):** Apply IPHC Regulatory Area allocation to the coastwide TCEY (if step 2 is omitted) or within each Biological Region to distribute the TCEY to IPHC Regulatory Areas. This management or policy decision may be informed by data or defined by an allocation agreement and may include different relative harvest rates by IPHC Regulatory Area. For example, recent trends in estimated all sizes WPUE from the modelled survey or fishery data, age composition, or size composition may be used to distribute the TCEY to IPHC Regulatory Areas. Inspection of historical trends in fishing intensity or catches by IPHC Regulatory Area may also be used. Additionally, predetermined fixed percentages are also an option. This allocation to IPHC Regulatory Areas may be a procedure with multiple adjustments using different information or agreements.

The steps described above would be contained within the IPHC Harvest Strategy Policy as part of the Management Procedure and are predetermined steps with a predictable outcome. The decision-making process would then occur (Figure 6).

4. **Annual Regulatory Area Adjustment (policy, *optional*)**: Adjust individual IPHC Regulatory Area TCEY limits to account for other factors as needed. This is the policy component of the harvest strategy policy and occurs as a final step where other objectives are considered (e.g., economic, social, etc.). A departure from the management procedure 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 could take advantage of current situations but may result in unpredictable longer-term outcomes.

The MSAB has defined coastwide and distribution elements of management procedures that are important for future evaluation, including the following listed in paragraph 42 of IPHC-2020-MSAB015-R.

> ***IPHC-2020-MSAB015-R, para. 42**.The MSAB **AGREED** that the following elements of interest for defining constraints on changes in the TCEY, and distribution procedures be considered for the Program of Work in 2020:*
>
> a) *constraints on the change in the TCEY can be applied annually or over multiple years at the coastwide or IPHC Regulatory Area level. Constraints on the change in TCEY currently considered include a maximum annual change in the TCEY of 15%, a slow-up fast down approach, multi-year mortality limits, and multi-year averages on abundance indices;*
>
> b) *indices of abundance in Biological Regions or IPHC Regulatory Area (e.g. O32 or All sizes from modelled survey results);*
>
> c) *a minimum TCEY for an IPHC Regulatory Area;*
>
> d) *defined shares by Biological Region, Management Zone, or IPHC Regulatory Area;*

e) *maximum coastwide fishing intensity (e.g. SPR equal to 36% or 40%) not to be exceeded when distributing the TCEY;*

f) *relative harvest rates between Biological Regions or IPHC Regulatory Areas.*

At MSAB014 and MSAB015, the three steps of a management procedure described above were formalized, and elements specifying candidate management procedures were defined for simulation and subsequent evaluation (Table 5, reproduced from IPHC-2020-MSAB015-R).

Table 5: Recommended management procedures to be evaluated by the MSAB in 2020 and the priority of investigation. A priority of 1 denotes a focus on producing precise performance metrics. A priority of 2 denotes potentially fewer simulations are desired, if time is constrained.

MP	Coastwide	Regional	IPHC Regulatory Area	Priority
MP 15-A	SPR 30:20		• O32 stock distribution • Proportional relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) • 1.65 Mlbs floor in 2A[1] • Formula percentage for 2B[2]	1
MP 15-B	SPR 30:20 MaxChange15%		• O32 stock distribution • Proportional relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) • 1.65 Mlbs floor in 2A[1] • Formula percentage for 2B[2]	1
MP 15-C	SPR 30:20 MaxChange15%	Biological Regions, O32 stock distribution Rel HRs[3]: R2=1, R3=1, R4=0.75, R4B=0.75	• O32 stock distribution • Relative harvest rates not applied • 1.65 Mlbs floor in 2A[1] • Formula percentage for 2B[2]	2
MP 15-D	SPR 30:20 MaxChange15% Max FI (36%)		First • O32 stock distribution • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) Second within buffer (pro-rated if exceeds buffer) • 1.65 Mlbs floor in 2A[1] • Formula percentage for 2B[2]	2
MP 15-E	SPR 30:20 MaxChange15%		• O32 stock distribution • Proportional relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) • 1.65 Mlbs floor in 2A[1]	2
MP 15-F	SPR 30:20 MaxChange15%	National Shares: 20% to 2B, 80% to other	• O32 stock distribution to areas other than 2B • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4)	1

MP	Coastwide	Regional	IPHC Regulatory Area	Priority
MP 15-G	SPR 30:20 MaxChange15%		• O32 stock distribution • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4)	1
MP 15-H	SPR 30:20 MaxChange15%		• O32 stock distribution • Relative harvest rates (1 for 2-3, 4A, 4CDE, 0.75 for 4B)	1
MP 15-I	SPR 30:20 MaxChange15%		• All sizes stock distribution • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4)	2
MP 15-J	SPR 30:20 MaxChange15%		• O32 stock distribution (5-year moving average) • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4)	1
MP 15-K	SPR 30:20 MaxChange15%		• 5-year shares determined from 5-year O32 stock distribution (vary over time but change only every 5th year)	2

[1] paragraph 97b IPHC-2020-AM096-R

[2] paragraph 97c of IPHC-2020-AM096-R

[3] R2 refers to Biological Region 2 (2A, 2B, 2C); R3 refers to Biological Region 3 (3A, 3B); R4 refers to Biological Region 4 (4A, 4CDE), and R4B refers to Biological Region 4B

2.2.2 Simulating management procedures

A major source of uncertainty in the management procedure is the generation of data. The data generation step simulates the process of observation by resampling from probability distributions that approximate the uncertainty in the observed data. Indices of abundance (NPUE and WPUE) are simulated using a lognormal distribution (Figure 7), while the proportion at age are simulated using a Dirichlet distribution (Figure 8). The nominal sample size was used as the scale parameter of the Dirichlet distribution, to control the variance of the distribution, i.e., a higher sample size implies lower variance. The nominal sample size is currently simulated assuming a fixed sampling proportion of the available abundance and is used as the input sample size for the estimation model data files. Alternative approaches to determine sample sizes and generate age-compositions will be explored as time allows.

The conditioned long and short coastwide OMs were used to verify the data generation code. Index data (NPUE and WPUE) generated from these OMs are similar to the data used in the 2019 stock assessment (Figure 7). The differences observed are due to the OM overestimating the numbers-at-age, compared to the stock assessment model, and to some small differences in the selectivity-at-age.

An example of how the simulated age composition from the long coastwide OM approximate the real data is shown in Figure 8, where the fit to the observed proportion at age from the survey is shown. The overall pattern is represented fairly well by the simulated data.

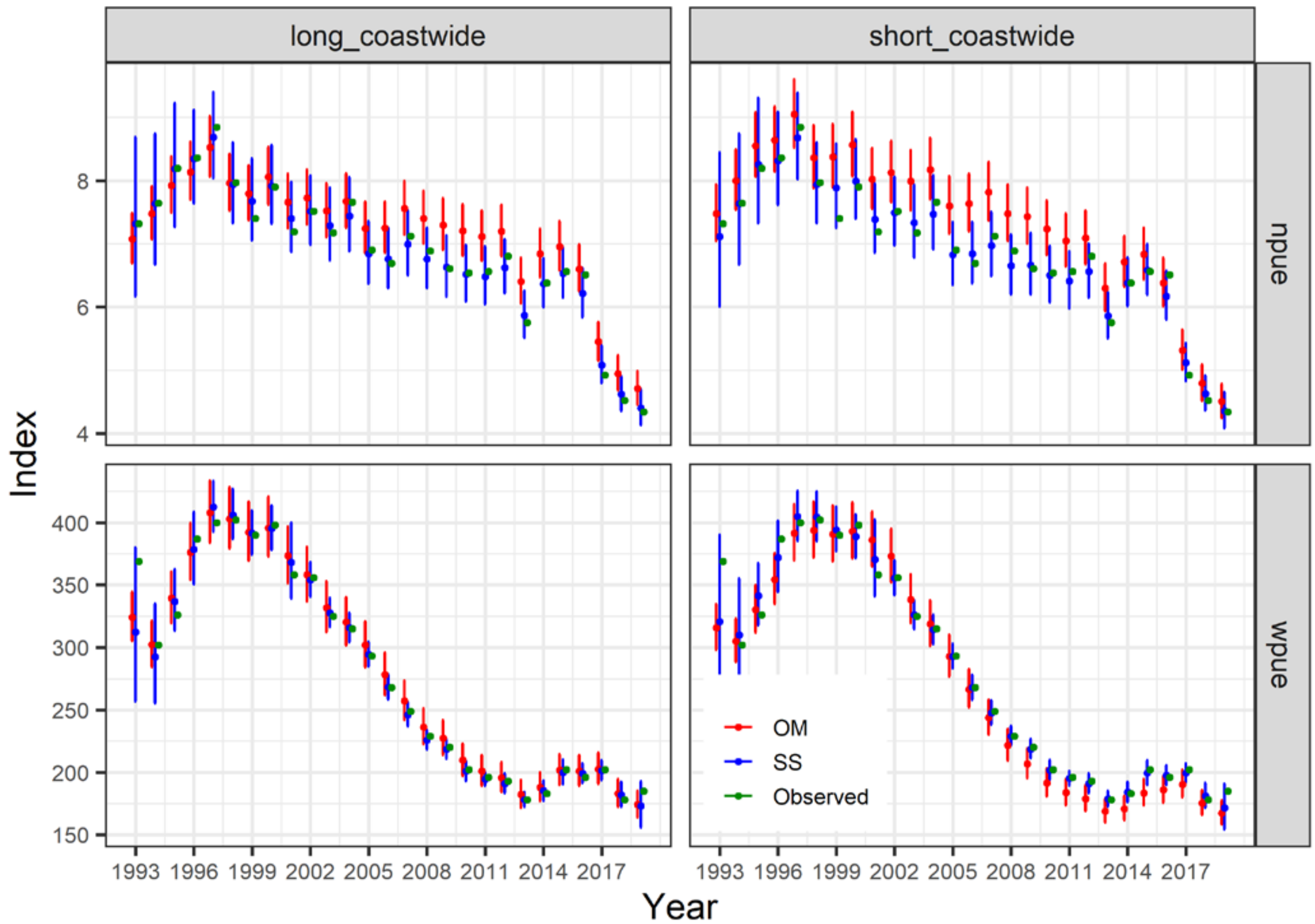

Figure 7: A comparison between simulated indices from long coastwide (panels to the left) and short coastwide (panels to the right) OMs (red lines) and estimated values from the long and short coastwide 2019 stock synthesis (SS) assessment models respectively (blue lines) for the survey NPUE (top panels) and the commercial WPUE (bottom panels). Modelled survey data (green points) from the sampling programs are included for reference.

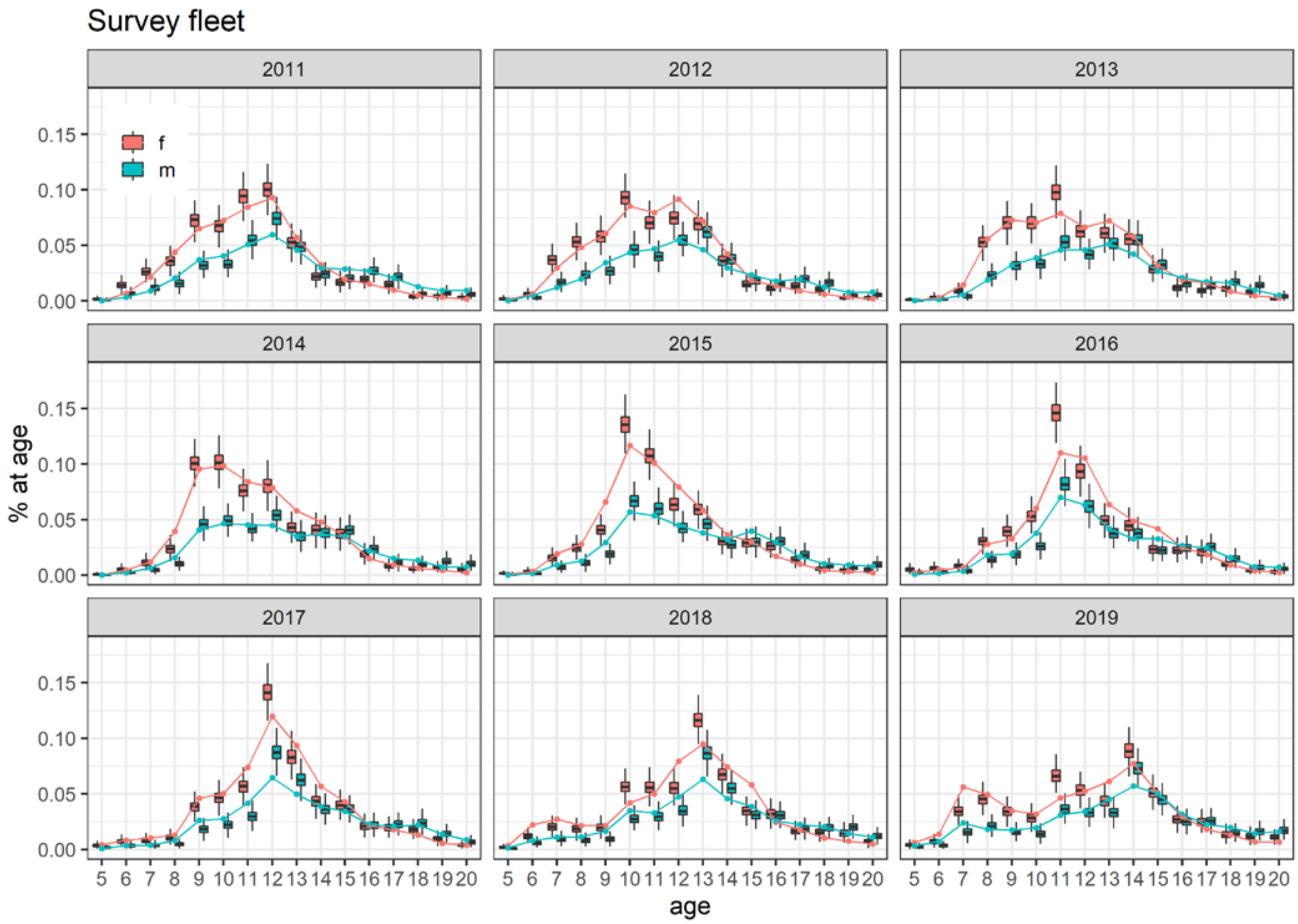

Figure 8: A comparison between simulated age compositions for ages 5 to 20 (boxplots) from the long coastwide OM and the observed data from the sampling program (lines/points) for the years 2011 to 2019. Females are represented in red, and males in blue.

These simulated data are then fed into two stock assessment models to approximate the stock assessment ensemble, the short and long coastwide models, implemented using stock synthesis but slightly simplified to reduce run time. Extensive testing showed that the averages of these two estimation models provide a reasonable approximation to the full stock assessment ensemble while reducing run times. Using actual stock assessment models will better characterize the variability than the simpler approach (autocorrelated estimation error about the true population values) used in the coastwide MSE for simulating estimation error.

The estimated values from the data generation and estimation model steps are used in the application of the harvest rule to determine mortality limits by IPHC Regulatory Area. The simulated application of the harvest rule will therefore include errors in the status as well as the size of the population, both of which will be propagated into management quantities.

3 RESULTS

Results presented here are related to testing the components of the management procedure, and the conditioning of a four-region operating model.

3.1 Management Procedure

The management procedure consists of three modules: data generation, estimation model, and harvest rule. Results from testing the estimation models and simulations using the full management procedure are reported here.

The short and long coastwide models used in the ensemble stock assessment require between one and seven minutes to estimate parameters without a Hessian. Estimation models used in a simulation framework need to be much faster. Therefore, to speed up these two estimation models, two approaches were used: reducing the reading time and reducing the computation time.

To reduce the reading time, the amount of data included in the model was reduced compared to the full assessment, while ensuring similar trajectories in the estimated quantities such as spawning stock biomass, exploitation and virgin biomass. Once this condition was met, the trend in dynamic B0 for the most recent period and the forecasted TM were also verified. The number of years of age composition data was shortened, and for each additional year of age data added during the projection period, an early year in the time series was removed. A minimum of at least 50 years of age composition for the directed commercial fleet is required before the removal of historical data begins. For the long coastwide estimation model, only the beginning of the CPUE time series was maintained, removing all subsequent years starting from 1994. Additionally, the start year of the long coastwide estimation model was set to 1935 instead of 1888.

To reduce the computation time, the ‘opt’ (optimized) version of stock synthesis was used, and the number of estimated parameters was reduced, mostly by removing some time-varying options which also increased the stability of the models. The remaining annual deviations in selectivity parameters were fixed at the values estimated by the original assessment model, and only the deviations for the most recent 10 years were left free to be estimated. In the first projected year, optimization was initiated using the parameters estimated by this streamlined version of the assessment model (i.e., the ‘ss.par’ file). For each subsequent year in the projection, the ‘ss.par’ file from the previous year was used, manually adding one extra parameter where necessary. The parameter estimation was also set to start from the last phase.

Finally, the convergence criteria was set to 0.1, the Hessian was not estimated (i.e., no uncertainty is calculated), and the amount of information printed on screen was reduced to a minimum. The number of iterations for a model to reach convergence was fixed to a maximum of 800. If the model did not converge after 800 iterations (i.e., convergence > 0.1), the initial value for the R0 parameter was increased by 5% and the model was restarted. If the model still did not converge, it was restarted for a third time, but estimation was started from phase 1. Extensive testing has resulted in major reductions in overall time required for estimation while still ensuring that every model converged when using this approach.

The two estimation models were called in parallel from an R script, which in turn was called by the C++ OM code. One-hundred-year projections for one MP takes slightly less than 1.5 hours on a laptop.

To test the performance of the EMs a simple projection experiment using simulated data from the long coastwide OM was performed. This experiment was designed to: 1) better understand the performance of the two models when projecting forward, given the streamlined approach taken; 2) to evaluate the approximate time needed to run each model with an increasing number of years; 3) to evaluate if convergence was achieved every time; and 4) to get an idea of the estimation error and its autocorrelation. Twenty datasets were generated from a single OM trajectory mimicking the long coastwide stock assessment. Indices were generated using a lognormal distribution with standard deviation equal to the average standard error in the indices of abundance from the last 5 years (i.e., commercial CPUE, log(SE) = 0.029; survey NPUE, log(SE) = 0.031). Age composition data were simulated using a Dirichlet distribution with the nominal sample size used in the stock assessment as a scale factor (see explanation in Section 2.2.2). An SPR of 0.43 was used and the closed loop simulation was run until the year 2100. The Root Mean Squared Error (RMSE) of the residuals was calculated for each simulation relative to the OM.

The estimation models closely replicate the trend in the OM population trajectory (Figure 9). The RMSE calculated from the average estimates of the two models fluctuated between 7.5% and 9.9% and the average across all simulations was equal to 8.8%. The inclusion of additional sources of variability in the OM (e.g., time varying weight-at-age, selectivity, movement, etc.) will likely increase the estimation error. An example is provided in Figure 10, where the long coastwide OM was projected forward with a time varying weight-at-age, as generated by the ARIMA process. The SSB estimates resulting from the average of the two EMs tended to deviate from the OM trajectory, especially in periods of relatively high or relatively low biomass. The standardized residuals show periods of overestimation alternating with periods of underestimation compared to the OM spawning biomass. The lag-1 autocorrelation of the residuals calculated over the whole projection period is equal to 0.974.

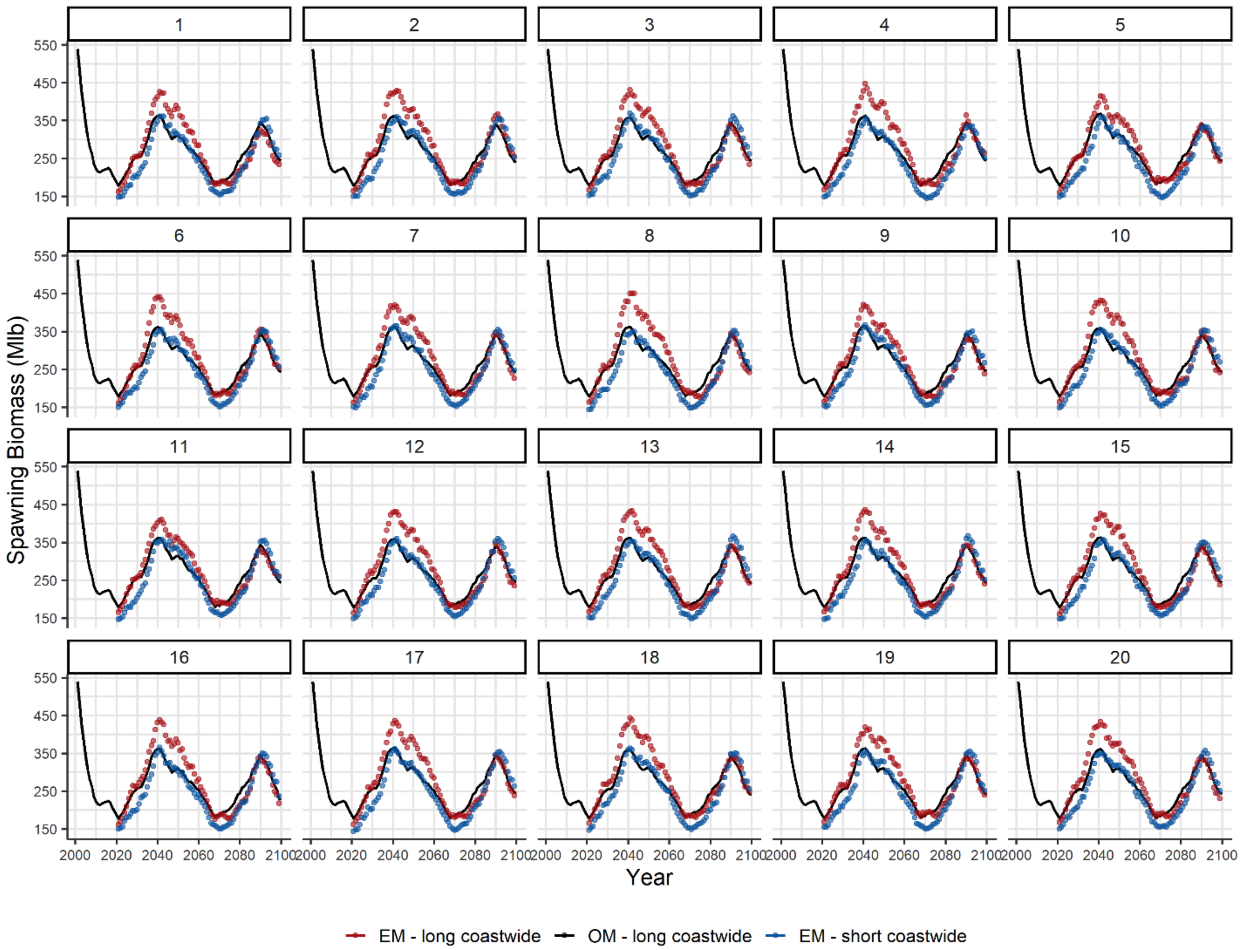

Figure 9: Simulated OM spawning biomass trajectory (black line) and estimated spawning biomass from the two estimation models (red and blue dots) for the twenty simulations generating different a dataset in each simulation.

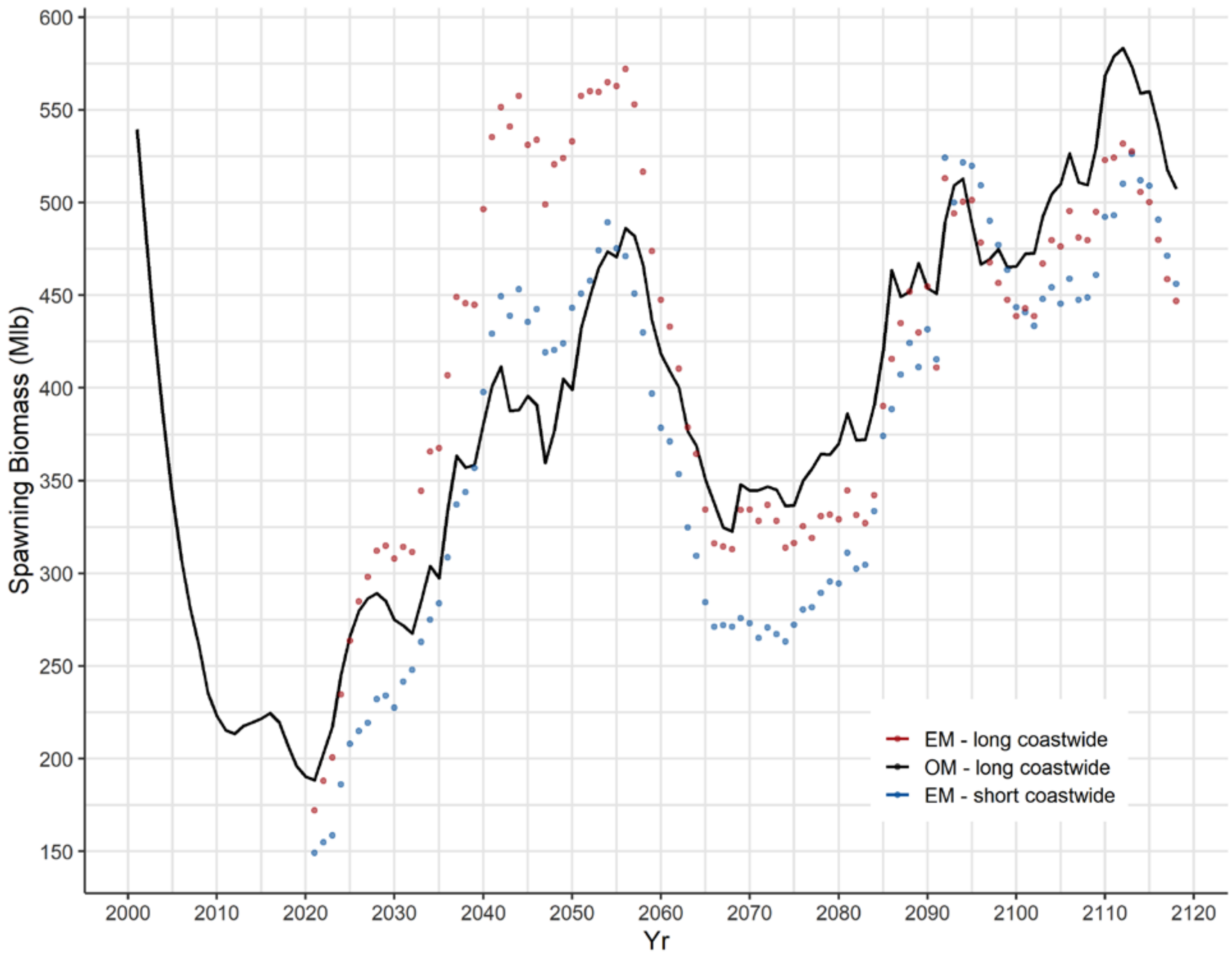

Figure 10: Simulated OM with time varying weight-at-age spawning biomass trajectory (black line) and estimated spawning biomass from the two estimation models (red and blue dots).

3.2 Four-region operating model

A multi-area OM was specified using the new framework, modeling four Biological Regions (2, 3, 4, and 4B; Figure 1), thirty-three (33) fisheries (Table 2), and four (4) surveys. The model was initiated in 1888 and initially parameterized using estimates from the long areas-as-fleets (AAF) assessment model. Selectivity was kept the same as the regional estimates from the long AAF assessment model except that the directed commercial and survey selectivities were made asymptotic (i.e., no descending limb) since movement in the spatially explicit OM accounted for availability among the Biological Regions.

Parameters for R0, proportion of recruitment to each Biological Region, movement from 2 to 3, 3 to 2, and 4 to 3 were estimated by minimizing an objective function based on lognormal likelihoods for spawning biomass predictions and region-specific modelled survey indices, and robustified multivariate normal likelihoods for the proportion of survey biomass in each region and observed proportions at age from the FISS. Other movement parameters were fixed to estimates from data (Figure 4: Estimates of movement rates by age from data (black solid circles) and fits (green circles) to those estimates using various functional forms described in Equations 1-4.) except that movement probabilities from 4 to 2, 2 to 4, 4B to 2, and 2 to 4B were set to zero for all ages. This makes the assumption that a Pacific halibut cannot travel between these areas in an annual time step even though significant probabilities of movement-at-age from 4 to 2 are predicted to occur from the data (Figure 4: Estimates of movement rates by age from data (black solid circles) and fits (green circles) to those estimates using various functional forms described in Equations 1-4.).

The OM was conditioned using five sets of observations: predicted spawning biomass from the long AAF stock assessment model (1888–2019), predicted spawning biomass from the stock assessment ensemble (1993–2019), survey indices of abundance for each Biological Region, survey proportions-at-age for each Biological Region, and the proportion of “all selected sizes” modelled survey biomass in each Biological Region (stock distribution). The lognormal likelihood (assuming that the observed value was the median) was used to fit to the predicted stock assessment spawning biomass and the survey indices.

$$-\ln(L) = \sum \left(\frac{\ln \left({O_y}/{E_y} \right)}{\sigma_y} \right)^2 \quad (5)$$

where O_y is the predicted spawning biomass from the stock assessment, E_y is the predicted spawning biomass from the OM, and σ_y is the standard deviation of the stock assessment spawning biomass on a natural log scale calculated as $\sigma_y = \sqrt{ln(1 + cv^2)}$.

A robustified multivariate normal (Fournier et al 1990, Starr et al 1999) was used to fit to the survey proportions-at-age and the regional stock distribution estimates.

$$-\ln(L) = -\sum \ln \left[\exp\left(\frac{-\left(O_y - E_y\right)^2}{2O_y'/N'} + 0.01 \right) \right] \quad (6)$$

where $O_y^{'} = (1 - O_y)O_y + 0.1/n$ and N' is the effective sample size as entered in the stock assessment (before data weighting). Estimates of uncertainty were available for the proportion of survey biomass in each Biological Region, thus the denominator was the standard deviation instead of O'_y/N'.

A subset of all possible parameters was used for conditioning by estimating the parameters that minimized the summed weighted negative log likelihood components for each observation type. The parameters estimated are listed in Table 6.

Table 6: Descriptions of the parameters estimated when conditioning the OM.

Parameters	# parameters	Description
$\ln(R_0)$	1	Natural log of unfished equilibrium recruitment. Determines the scale of the population trajectory.
$p_{y,r}^{R}$	3	Proportion of R_0 distributed to each Biological Region. Only three of the four parameters need to be estimated to sum to 1.
$\Psi_{2\rightarrow3}$	3, 4, or 5	Probability of movement-at-age from Region 2 to Region 3, modelled using an exponential or double exponential function (equations 2 and 3). The λs, minimum non-zero probability, maximum probabilities, and right asymptote were estimated. The age for the left peak was estimated by profiling over integer values and set equal to the same parameter in movement from 3 to 2.
$\Psi_{3\rightarrow2}$	Up to 6	Probability of movement-at-age from Region 3 to Region 2, modelled using a double-exponential function (equation 3). The left and right λs, left maximum probability, right maximum probability, and right asymptote were estimated. The age for the left peak was estimated by profiling over integer values and set equal to the same parameter in movement from 2 to 3.
$\Psi_{4\rightarrow3}$	Up to 6	Probability of movement-at-age from Region 4 to Region 3, modelled using a double-exponential function (equation 3). The right λ, left maximum probability, right maximum probability, and right asymptote were estimated.

Before estimating parameters, predictions from the OM were made using estimates from the long AAF stock assessment model movement-at-age as predicted from the functional forms fit to movement probabilities determined from data (Figure 4: Estimates of movement rates by age from data (black solid circles) and fits (green circles) to those estimates using various functional forms described in Equations 1-4.), and values of 0.073, 0.383, 0.526, 0.018 for the proportions recruited to Biological Regions 2, 3, 4, and 4B, respectively. The proportion of recruitment to each Biological Region was determined from initial investigations of various models and is similar to estimates from the final model presented below. Predictions of spawning biomass from this model approached zero at the end of the time-series (Figure 11: Predicted coastwide spawning biomass (top left), total biomass by Biological Region (bottom left), and the proportion of biomass in each Biological Region (right plots; Region 4B is denoted by “Region 5”) from the OM with initial parameters determined from the long AAF stock assessment models, movement-at-age as shown in Figure 4: Estimates of movement rates by age from data (black solid circles) and fits (green circles) to those estimates using various functional forms described in Equations

1-4., and *ad hoc* proportions of recruitment to each Biological Region. The blue line is predicted spawning biomass from the OM and red lines are the predicted spawning biomass from each model in the stock assessment ensemble and the red shaded area in the 90% credible interval from the ensemble stock assessment (top left). The proportion of biomass from the modelled survey results by year and Biological Region (filled circles) with estimated uncertainty are compared to the predicted proportion of biomass from the OM by year and Biological Region in the plots on the right.). Fits to the modelled survey indices and proportions-at-age were very poor.

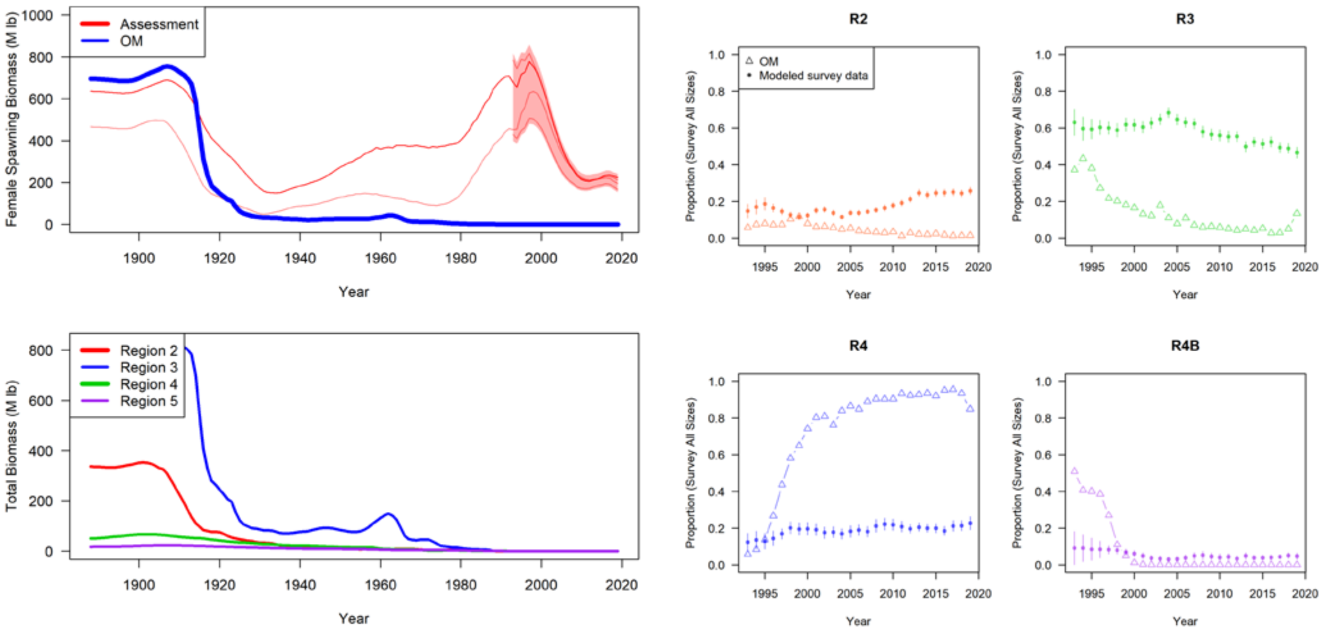

Figure 11: Predicted coastwide spawning biomass (top left), total biomass by Biological Region (bottom left), and the proportion of biomass in each Biological Region (right plots; Region 4B is denoted by "Region 5") from the OM with initial parameters determined from the long AAF stock assessment models, movement-at-age as shown in Figure 4: Estimates of movement rates by age from data (black solid circles) and fits (green circles) to those estimates using various functional forms described in Equations 1-4., and *ad hoc* proportions of recruitment to each Biological Region. The blue line is predicted spawning biomass from the OM and red lines are the predicted spawning biomass from each model in the stock assessment ensemble and the red shaded area in the 90% credible interval from the ensemble stock assessment (top left). The proportion of biomass from the modelled survey results by year and Biological Region (filled circles) with estimated uncertainty are compared to the predicted proportion of biomass from the OM by year and Biological Region in the plots on the right.

The parameters in Table 6 were fit to the five data sources individually to determine similarities and differences in the estimates of parameters and derived quantities that each data source implied. This was done for different parameterizations of movement to understand how changes to the structure affected the fit to the different data sets. Those results (not shown here) identified that fitting to the modelled survey distribution of biomass in each Biological Region was important because fitting to no other single data source resulted in a close prediction of the distribution.

Stock distribution is an important component of many management procedures to be tested, thus must be represented accurately by the conditioned OM. Secondly, fitting to index data resulted in predicted spawning biomass trajectories that were generally in the envelope of predicted spawning biomass from the stock assessment models. Index data are an important data source as they reflect trends in abundance by Biological Region. Fitting to proportion-at-age did not greatly improve the overall general trends in recent estimates of proportion-at-age in each region but did result in low predicted spawning biomass. Therefore, the final model was fit to the modelled survey proportion of biomass in each Biological Region and the modelled survey indices of abundance (NPUE) as used in the stock assessment, with each given equal weight in the joint likelihood.

The most parsimonious model with the best fits to all data sources, the most reasonable parameter estimates, and a balance between the fit to survey indices and stock distribution used the double exponential functions for movement from and to Biological Regions 4 to 3, 3 to 2, and 2 to 3. All non-integer parameters in these functions were estimated and the age at which the left peak occurs for movement from 3 to 2 and 2 to 3 was set equal for both and profiled over to determine the optimal value. Table 7 shows the likelihood values for each data source regardless if those data were used in the fitting process. Fits to predicted spawning biomass from the stock assessment models (even though not part of the total likelihood) and the index data were significantly improved with a peak movement parameter at age 6. The fit to the stock distribution was degraded slightly.

Table 7: Negative log-likelihood for each data source when fitting to individual data sources and weighted combinations of data. Numbers in red indicate that the data source was not used in the likelihood being minimized. The model with the left peak of movement-at-age equal to 6 (in bold) is the final model. Models fitting to only one data source (first five rows) set the left peak of movement-at-age equal to 6.

Model	Ensemble SB	Long AAF SB	Indices	Stock Distribution	Proportions-at-age
Ensemble SB only	1	638	207	358	-5382
Long AAF SB only	90	344	199	439	-5407
Indices only	257	1503	164	442	-5453
Distribution only	1715	14316	417	108	-5006
PropAtAge only	79	6781	750	358	-5575
movePeak4	40	2329	252	138	-5473
movePeak5	30	2117	228	137	-5560
movePeak6	**13**	**1333**	**219**	**141**	**-5524**
movePeak7	24	926	203	147	-5462
movePeak8	72	778	204	149	-5484

Table 8 shows the estimated proportion recruited to each Biological Region, which was very consistent regardless of the peak movement parameter.

The predicted spawning biomass fell mostly within the range of estimated spawning biomass from the four stock assessment models in the ensemble (Figure 12: Predicted coastwide spawning biomass (top left), total biomass by Biological Region (bottom left), and the proportion of biomass in each Biological Region (right plots; Region 4B is denoted by "Region 5") from the final OM. The blue line is predicted spawning biomass from the OM and red lines are the predicted spawning biomass from each model in the stock assessment ensemble and the red shaded area in the 90% credible interval from the ensemble stock assessment (top left). The proportion of biomass from the modelled survey results by year and Biological Region (filled circles) with estimated uncertainty are compared to the predicted proportion of biomass from the OM by year and Biological Region in the plots on the right). However, at the beginning of the time-series, the spawning biomass was greater than that in the "long" assessment models due to a large amount of predicted total biomass in Biological Region 3. The predicted stock distribution was very similar for most years, although the end of the time-series in Biological Regions 2 and 3 and beginning of the time-series in Biological Regions 4 and 4B show departures from this. These departures from the observed stock distribution were consistent for all models examined and suggest that the current structural specifications cannot capture these trends.

Table 8: Estimated proportion of recruitment in each Biological Region for various models and data sources being fit to.

Model	**2**	**3**	**4**	**4B**
Ensemble SB only	0.073	0.382	0.523	0.022
Long AAF SB only	0.075	0.417	0.507	<0.001
Indices only	0.068	0.362	0.503	0.067
Distribution only	0.075	0.380	0.535	0.010
PropAtAge only	0.071	0.384	0.527	0.018
movePeak4	0.072	0.384	0.527	0.017
movePeak5	0.072	0.383	0.529	0.016
movePeak6	0.071	0.384	0.527	0.018
movePeak7	0.073	0.383	0.525	0.019
movePeak8	0.071	0.382	0.529	0.018

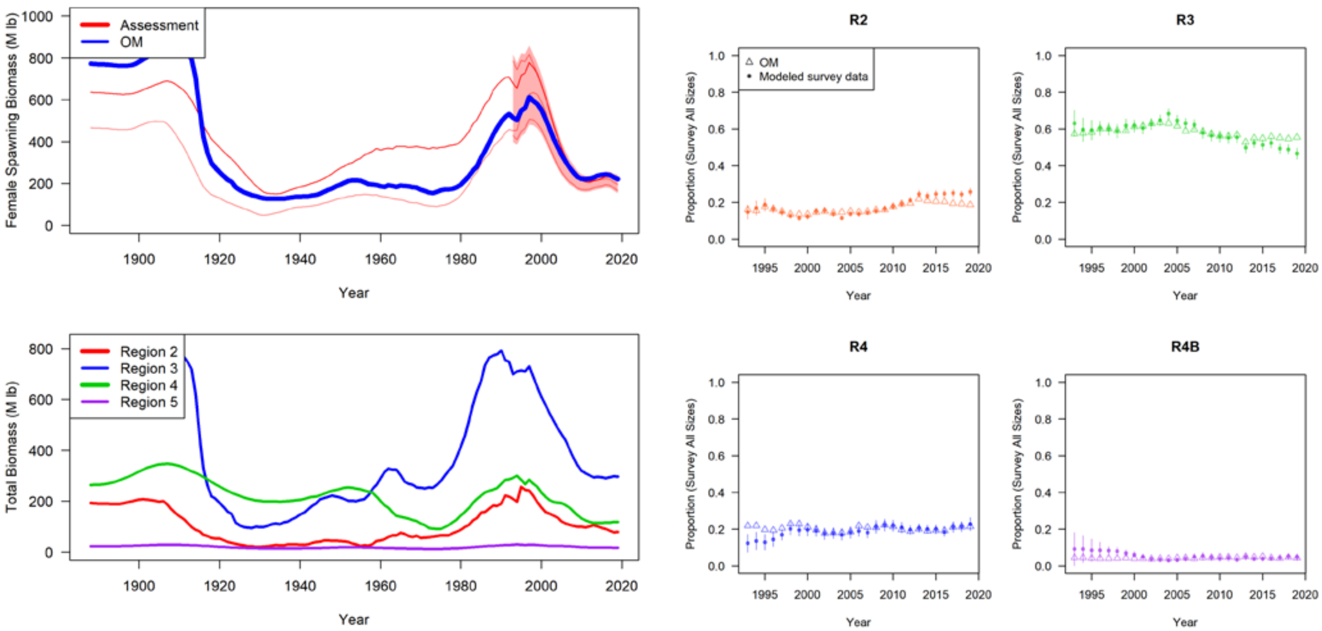

Figure 12: Predicted coastwide spawning biomass (top left), total biomass by Biological Region (bottom left), and the proportion of biomass in each Biological Region (right plots; Region 4B is denoted by "Region 5") from the final OM. The blue line is predicted spawning biomass from the OM and red lines are the predicted spawning biomass from each model in the stock assessment ensemble and the red shaded area in the 90% credible interval from the ensemble stock assessment (top left). The proportion of biomass from the modelled survey results by year and Biological Region (filled circles) with estimated uncertainty are compared to the predicted proportion of biomass from the OM by year and Biological Region in the plots on the right.

Fits to the modelled survey index were reasonable for Biological Regions 2, 3, and 4, but showed a pattern in residuals in Biological Region 4B (Figure 13). Few models that were examined were able to fit the time-series in Biological Region 4B, and those that did show an improved fit had poor fits to stock distribution and often a high estimated proportion of recruitment to 4B.

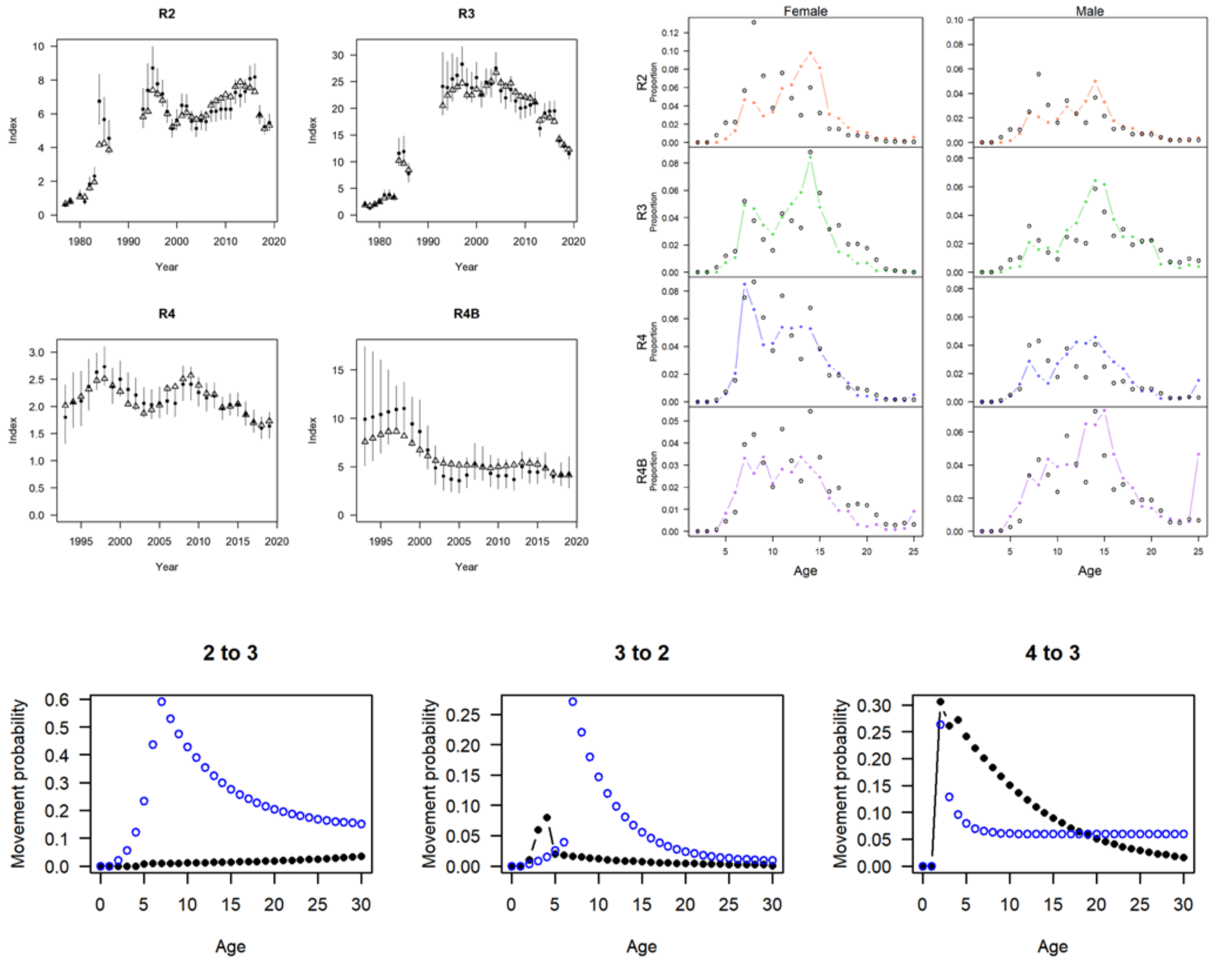

Figure 13: Fits to modelled survey NPUE index data (four panels on the top left), fits to proportions-at-age by sex and Biological Region from the year 2019 (eight panels on the top right), and estimated movement-at-age for the final OM (bottom row). Filled circles in the index plots are modelled survey NPUE with 95% credible intervals and the open triangles are predictions from the final OM. Filled circles connected by lines are the proportions-at-age determined from FISS data and the open circles are predictions from the final OM. The black filled circles are the movement-at-age probabilities determined from data and the open blue circles are estimated movement-at-age from the final OM.

The final OM shown here is a reasonable representation of the Pacific halibut population but has some shortcomings. For example, the lack of fit to the recent stock distribution (Figure 12) and the high predictions of young fish in Biological Region 2 in 2019 (Figure 13) are of concern. The lack of fit to the proportions-at-age in 2019 are balanced by reasonable fits in previous years, and the lack of fit to young ages begins to appear around 2011 (Figure 14). Similarly, the lack of fit to the stock distribution in Biological Regions 2 and 3 begins in 2012. There are a number of changes to the model and conditioning process that could be made to potentially improve these fits.

1. A change in the proportion recruited to each Biological Region (particularly 2 and 3) may have occurred around 2012. An environmental regime change occurred in 2014 (based on the Pacific Decadal Observation, PDO) and was used to model low and high recruitment regimes. The distribution of recruits could also be affected by these environmental regimes. Currently, the OM does not incorporate time-varying proportion of recruitment, but it will be added soon.
2. Movement-at-age may have changed between Biological Regions 2 and 3 around 2012 and may be linked to environmental regimes as well. Alternatively, movement probabilities may be a function of length instead of, or as well as, age, which is reasonable since the size of a fish can affect the distance they migrate. Recently, the weight-at-age of Pacific halibut has been low, indicating that the fish are smaller at age. This would necessitate modelling time-varying movement-at-age probabilities (as is done for selectivity). Currently, the OM does not incorporate time-varying movement, but it will be added soon.
3. Movement may be sex-specific, but tagging data are lacking this information.
4. A change in survey selectivity in Biological Region 2 may have occurred near 2012. This, however, is unlikely because the survey is standardized and has operated similarly each year since 1998.

Overall, the conditioned multi-region model is an appropriate starting point to simulate the population forward in time and test management strategies. Uncertainty will be captured by adding variability to the many processes (including movement) and/or incorporating scenarios to test specific cases or assumptions.

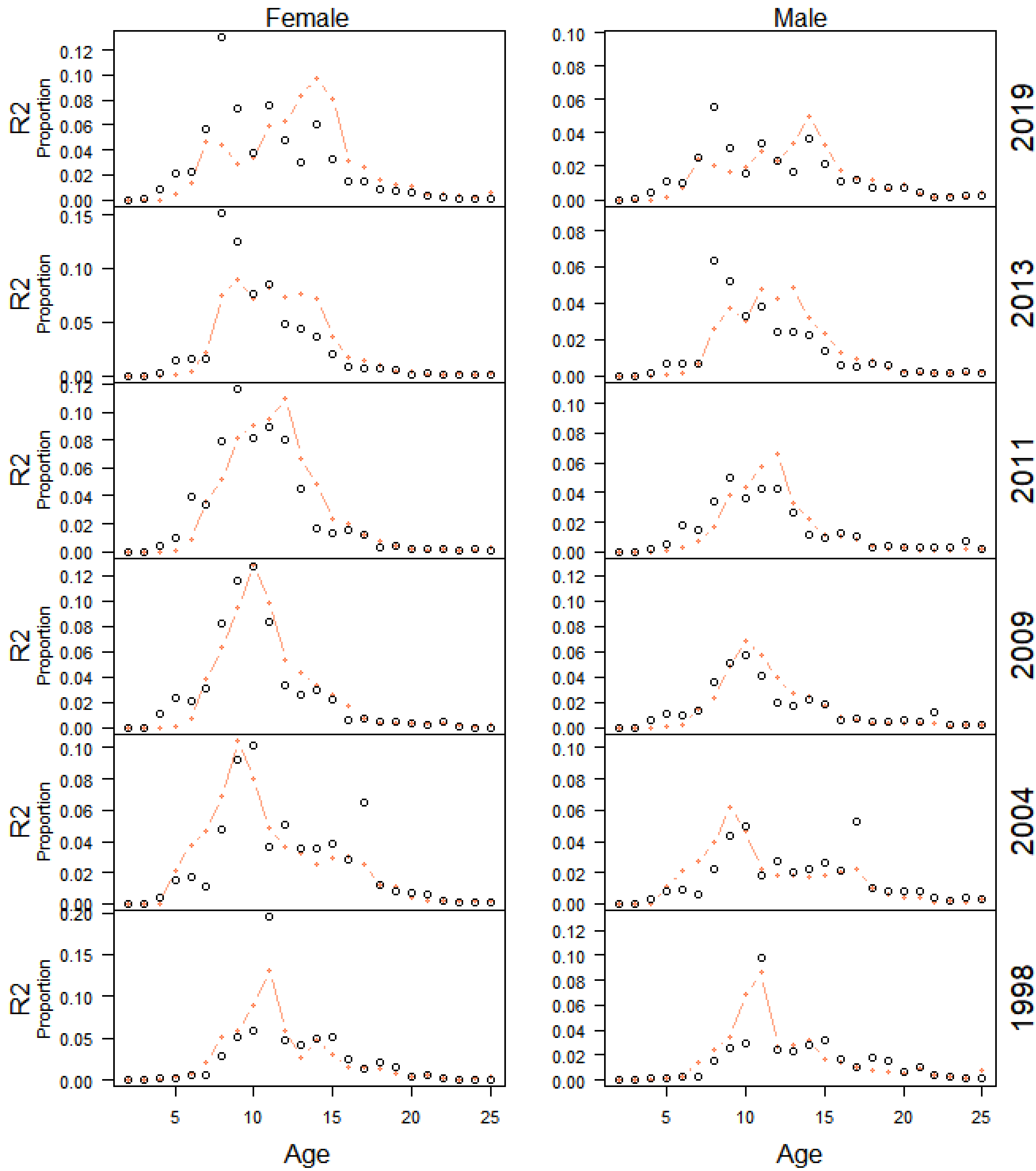

Figure 14: Fits to modelled survey proportions-at-age by sex in Biological Region 2 for various years from 1998 to 2019. Filled circles connect by lines are the proportions-at-age determined from FISS data and the open circles are predictions from the final OM.

4 PROGRAM OF WORK

Many important MSE tasks have already been completed; past accomplishments include the following:

1. Familiarization with the MSE process.
2. Defining conservation and fishery goals.
3. Defining objectives and performance metrics for those goals.
4. Developing coast-wide (single-area) and spatial (multiple-area) operating models.
5. Identifying management procedures for the coastwide fishing intensity and distributing the TCEY to IPHC Regulatory Areas.
6. Presentation of results investigating coastwide fishing intensity.

Management Strategy Evaluation is a process that can develop over many years with many iterations. It is also a process that needs monitoring and adjustments to make sure that management procedures are performing adequately. Therefore, the MSE work for Pacific halibut fisheries will be ongoing as new objectives are defined, more complex models are built, and results are updated. This time will include continued consultation with stakeholders and managers via the MSAB meetings, defining and refining goals and objectives, developing alternative operating models, running simulations, and reporting results. Along the way, there will be useful outcomes that may be used to improve existing management and will influence recommendations for future work. Embracing this iterative process, the program of work identifies the tasks to continue to make progress on the investigation of management strategies.

4.1 Five-year program of work

Eight (8) categories have been define in the five-year program of work (Figure 15).

Task 1: Review, update, and further define goals and objectives

Task 2: Develop performance metrics to evaluate objectives

Task 3: Identify realistic management procedures of interest to evaluate

Task 4: Design and code a closed-loop simulation framework

Task 5: Further the development of operating models

Task 6: Run closed-loop simulations and evaluate results

Task 7: Develop tools that will engage stakeholders and facilitate communication

Details of many tasks have not been specified beyond 2021, and the description below focuses on 2020 leading up to the 97th Annual Meeting (AM097) in January 2021.

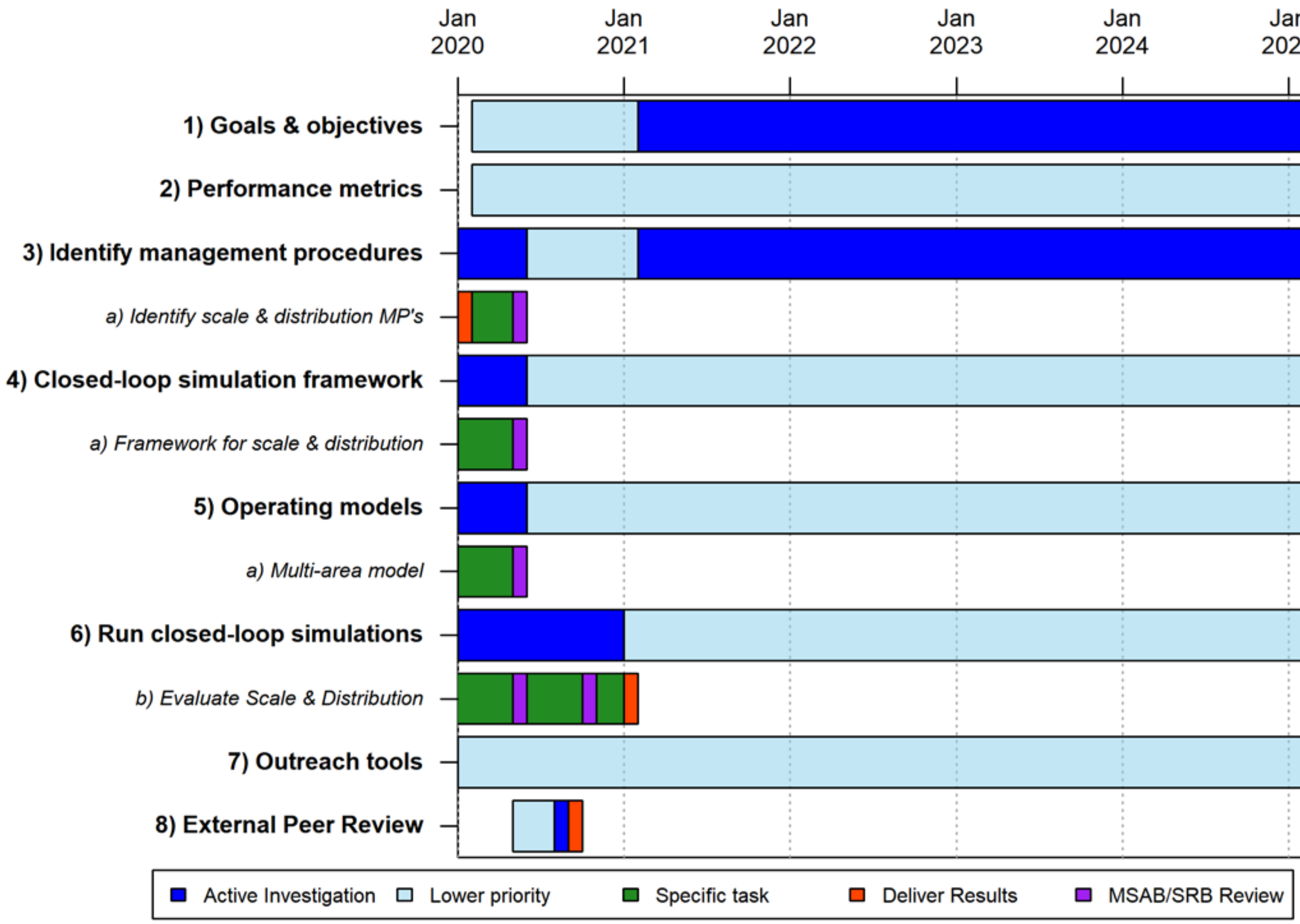

Figure 15: Gantt chart for the five-year work plan. Tasks are listed as rows. Dark blue indicates when the major portion of the main tasks work will be done. Light blue indicates when preliminary or continuing work on the main tasks will be done. Dark green indicates when the work on specific sub-topics will be done. Red areas show when results will be presented to the Commission. Purple areas show when the task will be reviewed by the MSAB and/or the SRB.

The first full MSE results incorporating coastwide scale and distribution components of the management procedure (Figure 6) will be presented at the 97th IPHC Annual Meeting (AM097) in January 2021. Therefore, results of simulations incorporating various management procedures based on the harvest strategy policy shown in Figure 6 will be reviewed by the SRB and evaluated by the MSAB in 2020. There are three main tasks to accomplish in 2020: 1) identify management procedures incorporating coastwide and distribution components to simulate, 2) condition a multi-area operating model and prepare a framework for closed-loop simulations, and 3) present results in various ways in order to evaluate the management procedures. These three main tasks are described below and Table 9 identifies the tasks that will be undertaken at each MSAB and SRB meeting in 2020.

Table 9: Tasks to complete in 2020 at the MSAB and SRB meetings.

May 2020 MSAB Meeting (MSAB015)	**Progress**
Review Goals and Objectives (Distribution & Scale)	Completed
Review simulation framework	Completed
Review multi-area model	Completed
Review preliminary results	
Identify MPs (Distribution & Scale)	Completed
June 2020 SRB Meeting (SRB016)	
Review simulation framework	
Review multi-area model	
Review preliminary results	
August 2020 MSAB Special Session	
Evaluate preliminary results	
September 2020 SRB Meeting (SRB017)	
Review penultimate results	
October 2020 MSAB Meeting (MSAB016)	
Review final results	
Provide recommendations on MPs for scale and distribution	
Annual Meeting 2021	
Presentation of first complete MSE product to the Commission Recommendations on Scale and Distribution MP	

5 RECOMMENDATIONS

That the SRB:

a) **NOTE** paper IPHC-2020-SRB016-08 Rev_1 which provides an update on the development of the IPHC MSE framework, a description of the specifications of the multi-area operating model, results from conditioning the multi-area operating model, and an overview of the implementation of management procedures.

b) **RECOMMEND** alternative specifications and additional features of the OM or general description of management procedures needed to evaluate management procedures related to coastwide scale and distribution of the TCEY in 2020.

c) **RECOMMEND** additional parameterizations and structural components to implement in the multi-area OM for use as an operating model in the MSE simulations for 2020.

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7 Appendices

Nil