IPHC-2020-MSAB016-08

Development of a framework to investigate fishing intensity and distributing the total constant exploitation yield (TCEY) for Pacific halibut fisheries

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PURPOSE

To provide an update of International Pacific Halibut Commission (IPHC) Management Strategy Evaluation (MSE) activities relating to 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 has developed a framework to 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 discard mortality, and is determined by the Commission at each Annual Meeting for each IPHC Regulatory Area.

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;
- integration with, use of, or comparison against stock assessment outputs or data;
- identification and development of management procedures with closed-loop feedback into the operating model;
- definition and calculation of performance metrics to evaluate the efficacy of applied management procedures.

Updates on the recent efforts in these areas are outlined in Section 2. Likewise, details on the software developed to perform these simulations are outlined in section 3.

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 1). Specifications of some elements are described below, with additional technical details in document IPHC-2020-MSAB016-INF01.

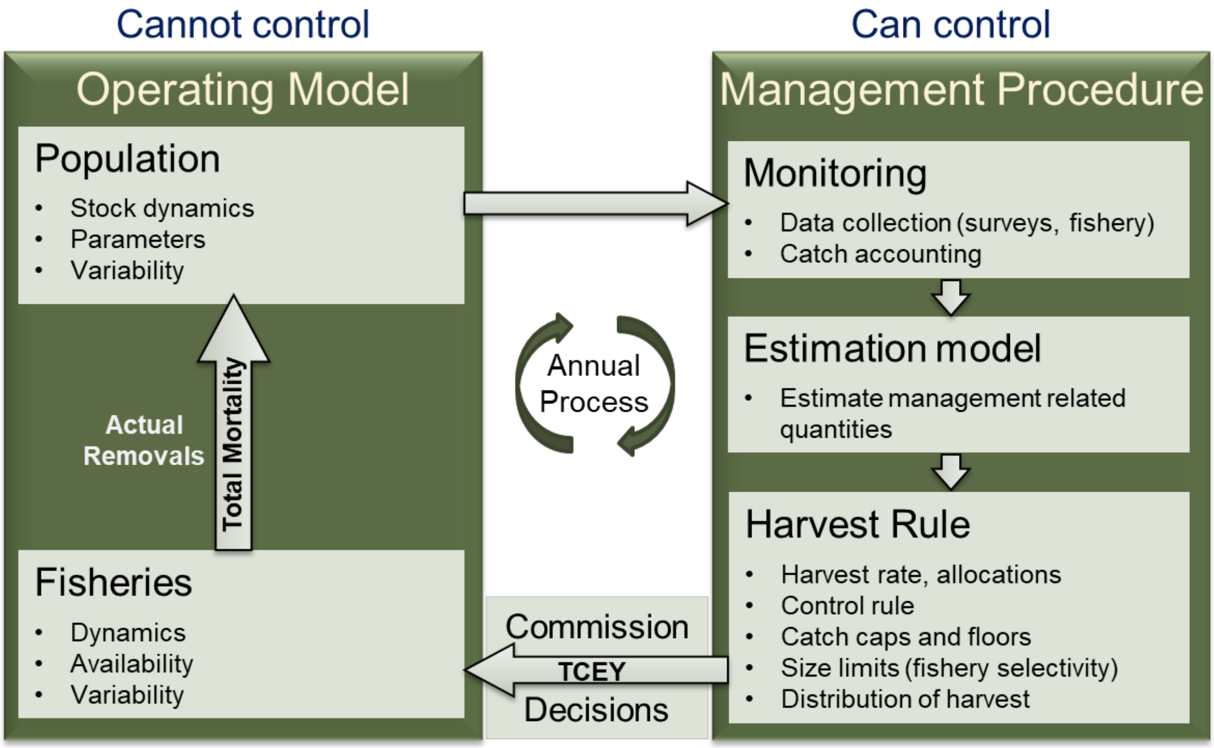

Figure 1: Illustration of the closed-loop simulation framework with the operating model (OM) and the Management Procedure (MP). This is the annual process on a yearly timescale.

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 2) 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 does not currently perform estimation or optimisation but will be a very useful tool for many investigations of the Pacific halibut fishery in the future.

2.1.1 General process of 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 specified and most can vary over time, region, sex, fishery, and age where relevant.

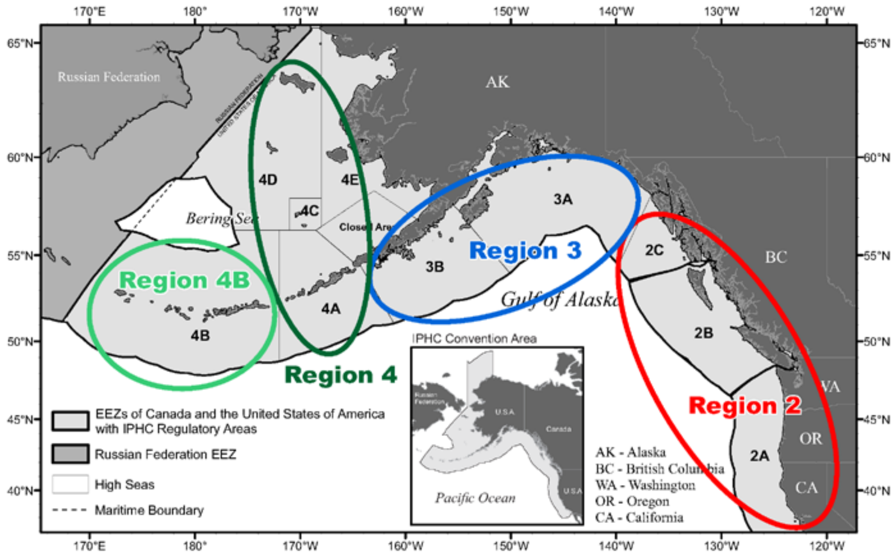

Figure 2: Biological Regions overlaid on IPHC Regulatory Areas. Region 2 comprises 2A, 2B, and 2C, Region 3 comprises 3A and 3B, Region 4 comprises 4A and 4CDE, and Region 4B comprises solely 4B.

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 from this point that closed-loop simulations, called the “projection period,” begin.

A script written in the R statistical language (R Core Team 2020) containing all the details of the management procedure being evaluated is called during the projection period, which does the following. It reads the current OM state from ‘csv’ files written by the OM. It generates data with observation error that are needed for estimation models (EMs) and MPs. It runs the estimation models, if required, to determine mortality limits and realized mortality for each fishery. The mortalities for each fishery feed back into the OM along with other projected annual processes (e.g., weight-at-age) to simulate the fish population one year forward. Weight-at-age for the projection year is generated before starting the simulations as a random process, as described in section 2.1.7.2 and in IPHC-2020-MSAB015-08.

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).

Biological Regions (Figure 2) were therefore 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. It is unlikely that there is a set of Regions that accurately delineates the stock biologically since different aspects of the stock differ over varying scales, biological boundaries may shift over time, and movement occurs among Biological Regions.

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 an appropriate and 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 selectivities 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. However, if a fishery does not interact with the pool of fish in a Biological Region, harvest rates determined for each fishery may be inaccurate because the biomass to which selectivity is applied would be incorrect, and some fisheries may intercept ages/sizes of Pacific halibut that they commonly do not interact with. This is unlikely to occur and will have very little effect on the results of this MSE because harvest rates are not explicitly used in the management procedures (mortality limits are used for management) and similarity of age/size compositions were used to define Biological Regions.

Additionally, calculating statistics specific to IPHC Regulatory Areas requires assumptions about distribution of biomass within a 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 objectives related to IPHC Regulatory Area 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. 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 determining proportions from historically observed distributions 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 for five general sectors consistent with the definitions in the recent IPHC stock assessment (IPHC-2020-SA-01):

- **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** 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 realized from 1992 through 2019 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. Darker colors indicate higher values.

Year	2A	2B	2C	3A	3B	4A	4CDE	4B
Commercial	17.5	259.8	205.5	551.2	252.4	78.2	72.5	62.8
Sublegal discards	0.5	7.1	5.2	16.7	10.7	2.1	1.3	0.8
Non-directed discard mortality	11.8	12	4.5	73.6	36.2	39.2	128.6	16.2
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	0.6	<0.1	2.4

2.1.3 Maturity

Spawning biomass for Pacific halibut is currently calculated from 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 they are not modelled, but could be added. Stewart & Hicks (2017) examined the sensitivity 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. Ongoing research on maturity and skip spawning will help to inform future implementations of the basis for variability in the determination of spawning output.

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-01) and as described in detail in Stewart and Martell (2016). Smoothed observations of weight-at-age from NMFS trawl surveys were used to augment ages 1-7 fishery and survey weights-at-age. 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.

Table 2: The twenty-five 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 Mlbs	2019 Mortality tonnes
Directed Commercial2A	2A	0.89	404
Directed Commercial 2B	2B	5.22	2,368
Directed Commercial 2C	2C	3.67	1,665
Directed Commercial 3A	3A	8.16	3,701
Directed Commercial 3B	3B	2.31	1,048
Directed Commercial 4A	4A	1.45	658
Directed Commercial 4B*	4B	1.00	454
Directed Commercial 4CDE	4CDE	1.65	748
Directed Commercial Discards 2A	2A	0.03	14
Directed Commercial Discards 2B	2B	0.13	59
Directed Commercial Discards 2C	2C	0.06	27
Directed Commercial Discards 3A	3A	0.32	145
Directed Commercial Discards 3B	3B	0.15	68
Directed Commercial Discards 4A	4A	0.09	41
Directed Commercial Discards 4B	4B	0.03	14
Directed Commercial Discards 4CDE	4CDE	0.07	32
Non-directed Commercial Discards 2A	2A	0.13	59
Non-directed Commercial Discards 2B	2B	0.24	109
Non-directed Commercial Discards 2C	2C	0.09	41
Non-directed Commercial Discards 3A	3A	1.65	748
Non-directed Commercial Discards 3B	3B	0.48	218
Non-directed Commercial Discards 4A	4A	0.35	159
Non-directed Commercial Discards 4CDE	4CDE	3.50	1,588
Non-directed Commercial Discards 4B	4B	0.15	68
Recreational 2B	2B	0.86	390
Recreational 2C	2C	1.89	857
Recreational 3A	3A	3.69	1,674
Subsistence 2B	2B	0.41	186
Subsistence 2C	2C	0.37	168
Subsistence 3A	3A	0.19	86
Recreational/Subsistence 2A	2A	0.48	218
Recreational/Subsistence 3B	3B	0.02	9
Recreational/Subsistence 4	4A, 4CDE	0.06	27

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

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.

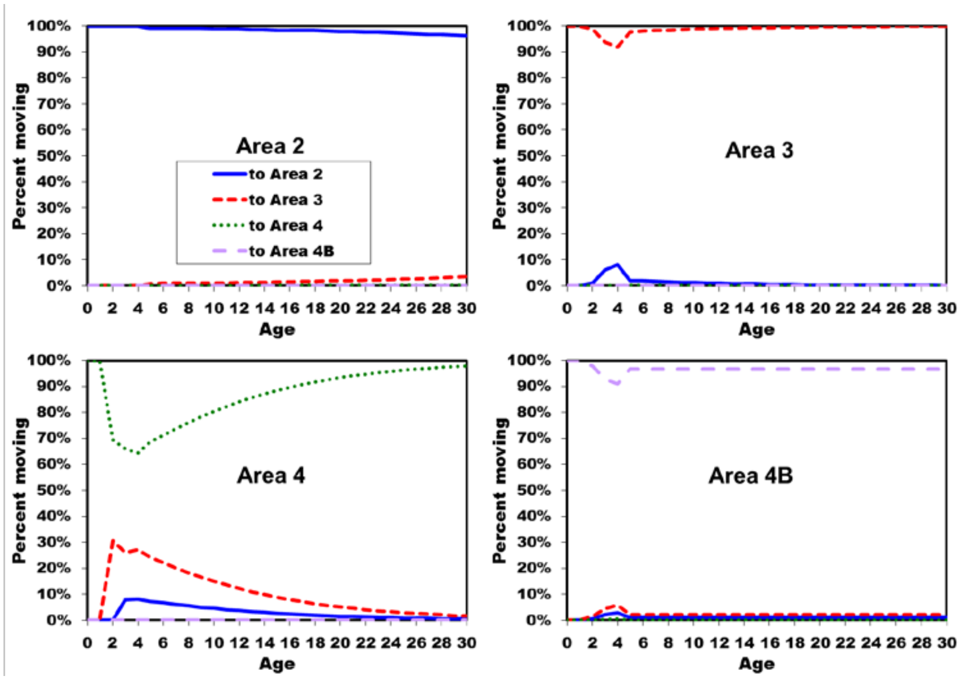

Figure 3: Estimated aggregate annual movement rates by age from Biological Regions (panels) based on currently available data (from IPHC-2019-AM095-08).

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 age 2-4 to/from Region 4 are similar to those observed for 2-4-year-old Pacific halibut compared to older Pacific halibut in Region 3.

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 is 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.

2.1.6 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 encountered 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.

Parameters for selectivity and retention 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.

2.1.7 Uncertainty in the operating model

Uncertainty is important to consider, as the goal of an MSE is to develop management procedures that are robust to uncertainty. 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. Parameters vary between simulated trajectories and are drawn from correlated probability distributions that are derived from the stock assessment models when conditioning the OM. These sets of parameters resulted in multiple historical population trajectories from which to begin the projections. The major sources of uncertainty in the OM are described in Table 3.

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

Process	**Uncertainty**
Natural Mortality (M)	Variability determined from assessment
Average recruitment (R_0)	Effect of the coastwide environmental regime shift and variability determined from conditioning
Recruitment	Random lognormal deviations. Variability on distribution to Biological Regions determined from conditioning
Movement	Change in parameters synchronized with PDO regime shift

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**
Average recruitment (R_0)	Effect of the coastwide environmental regime shift, modelled as an autocorrelated indicator based on properties of the PDO
Recruitment	Random lognormal deviations. Variability on distribution to Biological Regions.
Movement	Variability on movement parameters determined from conditioning process
Size-at-age	Annual and cohort deviations in weight-at-age by Biological Region, with approximate historical bounds
Sector mortality	Sector mortality allocation variability on non-directed commercial discard mortality, directed discard mortality, and unguided recreational mortality within an area
Movement	Change in parameters synchronized with PDO regime shift

Projected weight-at-age

It is important to simulate time-varying weight-at-age because it is an influential contributor to the yield and status of Pacific halibut. Weight-at-age varies over time historically, and the projections capture that variation using a random walk from the previous year. This variability was implemented using the same general procedure as in the coastwide MSE (IPHC-2018-MSAB011-08), with a few modifications to allow for slight departures between regions and fisheries. The method is described in IPHC-2020-MSAB015-08.

Linkage between average recruitment and environmental conditions

The average recruitment (R_0) is related to the Pacific Decadal Oscillation index[1], 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 was determined from the stock assessment.

The regime was simulated in the MSE by generating a 0 or 1 to indicate the regime in that future year, as described in IPHC-2018-MSAB011-08. 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 recent years. However, the probability of changing to the opposite regime was a function of the length of the current regime with a probability of changing being 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 or greater than 30 years.

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

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. The third component is the estimation of mortality, which is likely to deviate from the actual realize mortality. This is an important component to consider especially if catch accounting is inaccurate and subject to bias.

The second component (realized mortality) is implemented in the OM for the non-directed discard mortality, the directed discard mortality, subsistence mortality, and the unguided recreational mortality. The methodology used to simulate this variability for these sectors is described in Section 2.3.2. All other sectors (i.e. recreational and commercial) are assumed to achieve the mortality limits every year.

2.2 Four-region operating model

A multi-area OM was specified with four Biological Regions (2, 3, 4, and 4B; Figure 2), 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. 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. Other movement parameters were fixed to estimates from data (Figure 3) 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 3).

The OM was conditioned using five sets of observations: the average predicted spawning biomass from the long AAF and long coastwide stock assessment models (1888–1992), 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).

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 5.

Table 5: Descriptions of the parameters estimated when conditioning the OM. Separate sets of parameters were estimated for movement in poor and good PDO regimes.

Parameters	# parameters	Description
$\ln(R_0)$	1	Natural log of unfished equilibrium recruitment. Determines the scale of the population trajectory.
$p^R_{y,r}$	3	Proportion of R_0 distributed to each Biological Region. Only three of the four parameters need to be estimated to sum to 1.
$\Psi_{2\to3}$	5 + 5	Probability of movement-at-age from Region 2 to Region 3, modelled using a double exponential function (equation 3). The left and right λs, left maximum probability, right maximum probability, and right asymptote were estimated.
$\Psi_{3\to2}$	5 + 5	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.
$\Psi_{4\to3}$	5 + 5	Probability of movement-at-age from Region 4 to Region 3, 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 parameters in Table 5 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, the modelled survey indices of abundance (NPUE) as used in the stock assessment, the estimated spawning biomass from 1888 to 1992 from the two long assessment models, and the estimated spawning biomass from the ensemble assessment from 1993–2019 with each given *ad hoc* weights of 1.0, 0.1, 0.4, and 0.4, respectively, in the joint likelihood.

The predicted spawning biomass fell mostly within the range of estimated spawning biomass from the four stock assessment models in the ensemble (Figure 4). The multi-region operating model predicted a female spawning biomass at the upper part and slightly above the 90% credible interval from about 1930 to 1960 for the long assessment models due to a large amount of predicted total biomass in Biological Regions 3 and 4. The predicted stock distribution matched closely 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 showed departures. These departures from the observed stock distribution were consistent for all models examined and suggest that the current structural specifications cannot capture these trends.

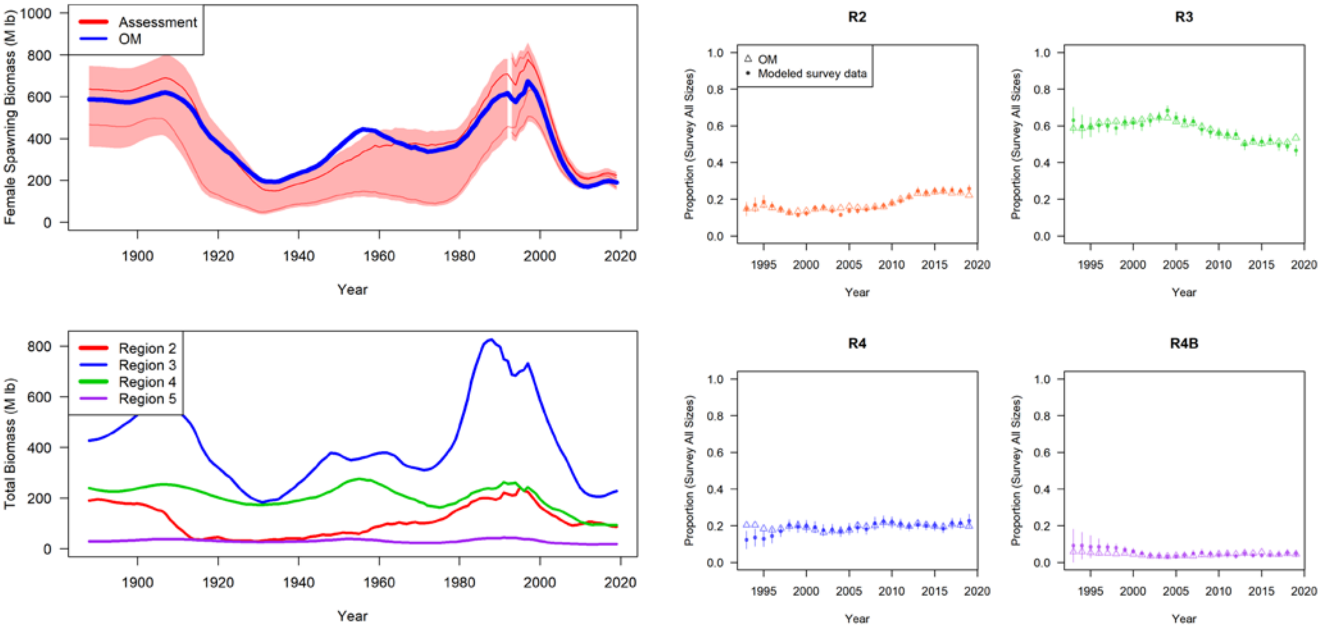

Figure 4: Predicted coastwide spawning biomass (top left), total biomass by Biological Region (bottom left), and the proportion of biomass in each Biological Region (right plots; Region 4B is denoted by "Region 5") from the final OM. The blue line is predicted spawning biomass from the OM and red lines 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 all Biological Regions, but showed some patterns in residuals in Biological Region 2 (Figure 5). Few models that were examined were able to fit the time-series in Biological Region 2 much better, and those that did show an improved fit had poor fits to stock distribution.

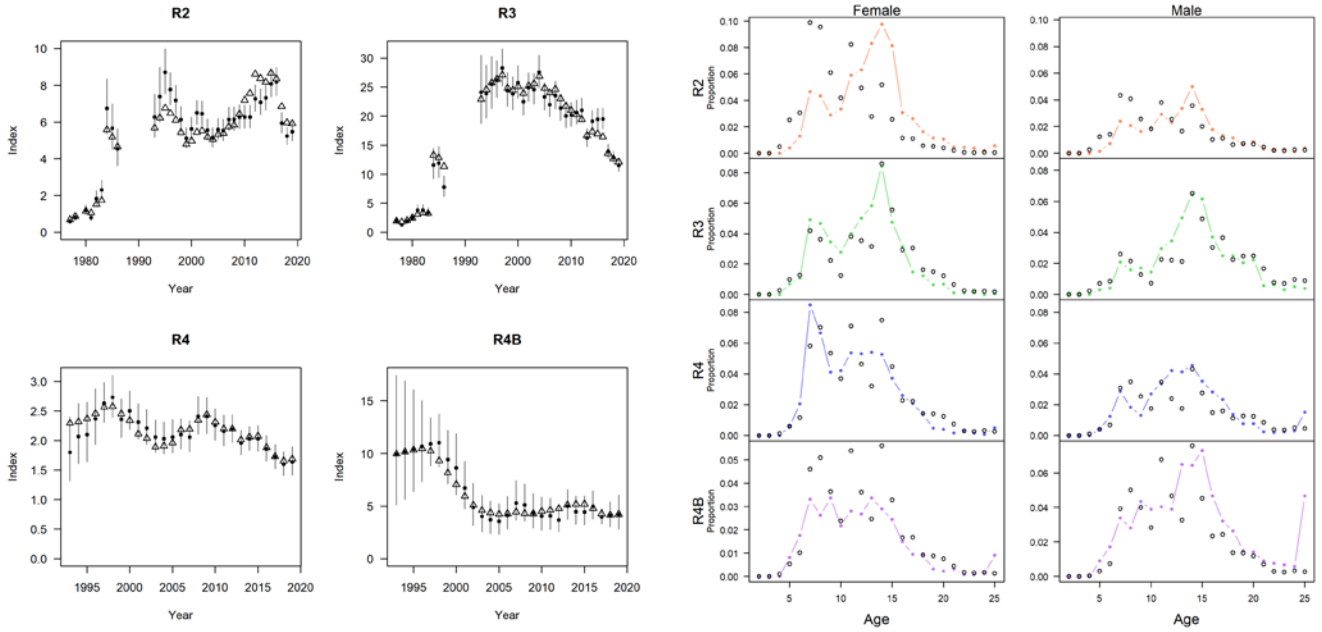

Figure 5: Fits to modelled survey NPUE index data (four panels on the top left), fits to proportions-at-age by sex and Biological Region from the year 2019 (eight panels on the top right), and estimated movement-at-age for the final OM (bottom row). Filled circles in the index plots are modelled survey 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.

Estimated and assumed movement probabilities-at-age from one Biological Region to another are shown in Figure 6. Movement from 2 to 3 is estimated to be much greater than the data suggest with higher movement of very young fish and lower movement rates of older fish during high PDO regimes. The generally higher movement of older fish from 2 to 3 may be to counter-balance the high movement rates of young fish from 3 to 2. The OM has movement rates near 5% for movement of older fish from 3 to 2. Younger fish tend to move at higher rates from 4 to 3 with little movement once they are age 8 and older. The OM assumes that this is a closed population with no movement in or out of the four Biological Regions, which may explain some of the differences observed from the movement rates based on observations.

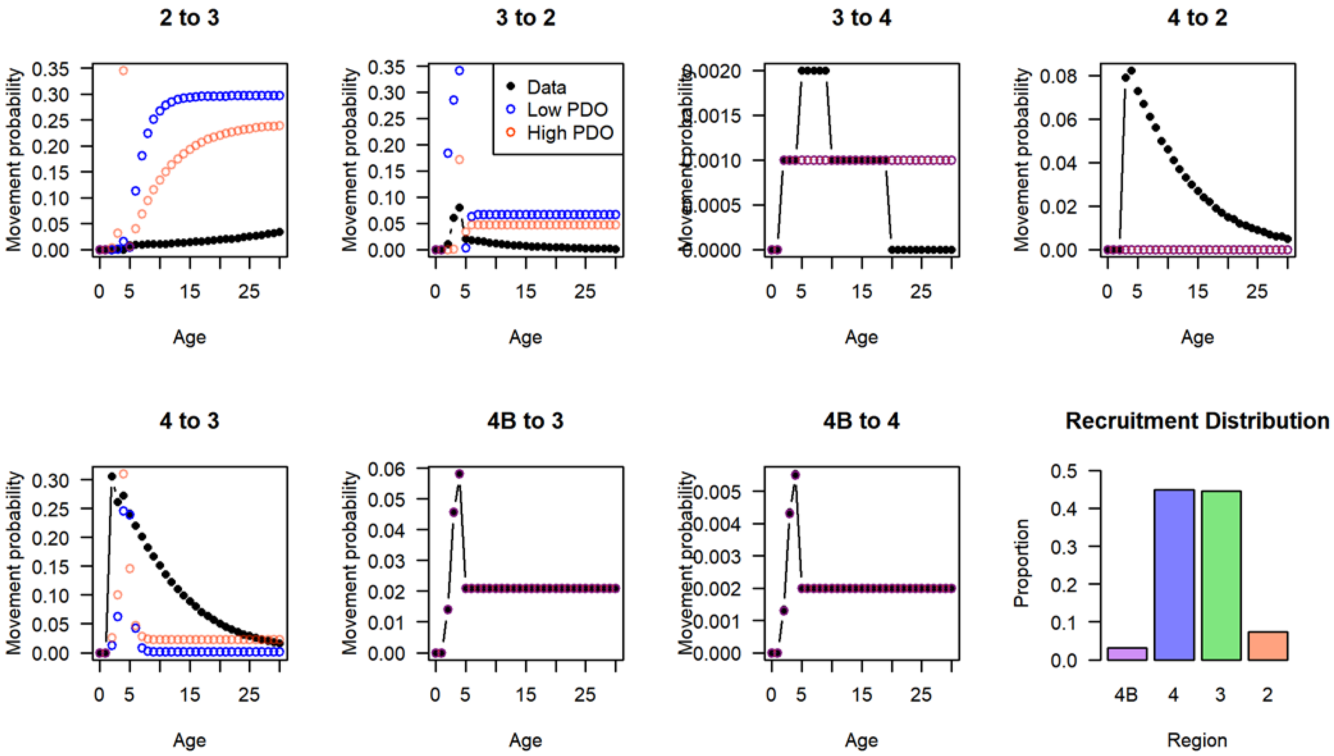

Figure 6: Probabilities of movement-at-age from the data and assumptions (Figure 3) and the conditioned OM (blue and red circles for low and high PDO regimes, respectively). The proportion of recruitment distributed to each Biological Region is shown in the lower right.

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 2019 stock distribution in Biological Regions 2 and 3 (Figure 4) and the high predictions of young fish in Biological Region 2 in 2019 (Figure 5). The lack of fit to the proportions-at-age in 2019 are balanced by better fits in previous years (not shown). There are many changes to the model and conditioning process that could be made to potentially improve these fits. For example, movement may be sex-specific, but tagging data are lacking this information.

Overall, the conditioned multi-region model represents the general trends of the Pacific halibut population and is a useful model to simulate the population forward in time and test management strategies.

2.2.1 Uncertainty in the four-region operating model

Uncertainty in population trajectories was captured by adding variability to the parameters of the operating model as specified in Table 3. The correlation matrix estimated from the long AAF model for the R_0, natural mortality (female and male), and recruitment deviations was combined with the correlation matrix for the movement and recruitment distribution parameters as estimated from the conditioning process. The R_0 parameter was estimated in both models and correlations with R_0 were available for all parameters. Otherwise only the correlations for the parameters within a model were available. Parameters were drawn from a multivariate normal distribution to add variability. Correlations and standard deviations for the movement and recruitment distribution parameters were divided by 4 to ensure that the covariance matrix was invertible and to avoid large deviations in movement that may have unknown and undesirable consequences. Hypotheses of movement extremely different than the OM will be investigated through sensitivities and robustness tests.

Fifty trajectories of the OM with parameter variability show a wider range than the 90% credible interval from the ensemble stock assessment (Figure 7). Prior to 1993, the trajectories are in and above the upper portion of the ensemble assessment 90% credible interval, but from 1993 to 2019 the trajectories encompass and extend beyond the credible interval. Therefore, the OM is a reasonable representation of the Pacific halibut population in recent decades and is modelled with variability that will allow for the robust testing of MPs.

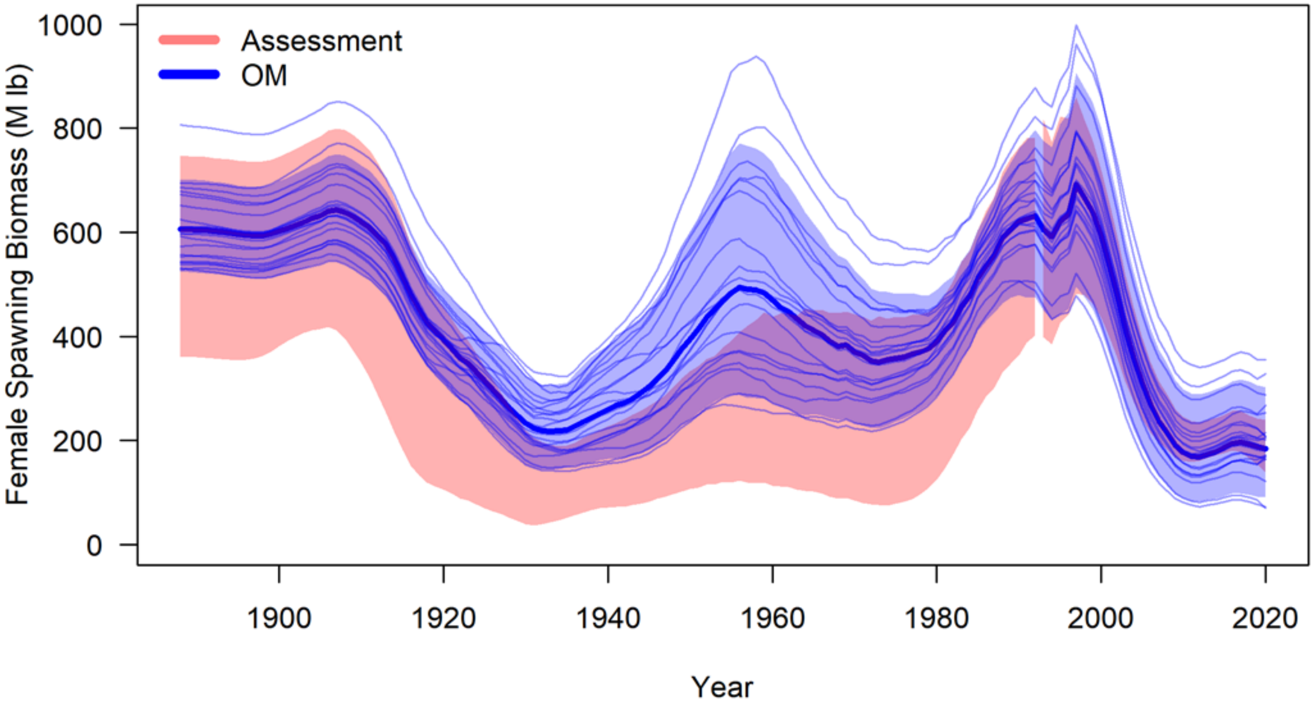

Figure 7: The 90% credible interval from six-hundred trajectories of the OM with parameter variability included (blue shaded area), shown against the 90% credible interval of the ensemble stock assessment (two models before 1993 and four models for 1993–2019, red shaded area). An example twenty trajectories are shown (thin blue lines) along with the median of all 600 trajectories (thick blue line).

The stock distribution with variability does not show a large departure from the observed stock distribution (Figure 8). The variability is consistent with the observations except at the beginning of the time-series in Biological Region 4 and in 2019 for Biological Regions 2 and 3. The beginning of the time-series in Biological Region 4 was estimated with few data. The recent year may have seen a shift in movement that is not explained by the OM.

Projections with the OM incorporated parameter variability (Table 3) and projection variability (Table 4) produced a wide range of trajectories. Figure 9 shows the median of six-hundred simulations to 2119 without mortality due to fishing, along with the interval between the 5th and 95th percentiles. Individual trajectories (twenty plotted) show that a single trajectory may cover a wide range of that interval in this 100-year period. The variability looks like it has reached its full range after 30 years, although there is an increasing trend near year 2090. This may occur because without fishing, some trajectories may take a long time to recover to unfished conditions when starting at low values. It is likely that with fishing, the spawning biomass equilibrates much faster.

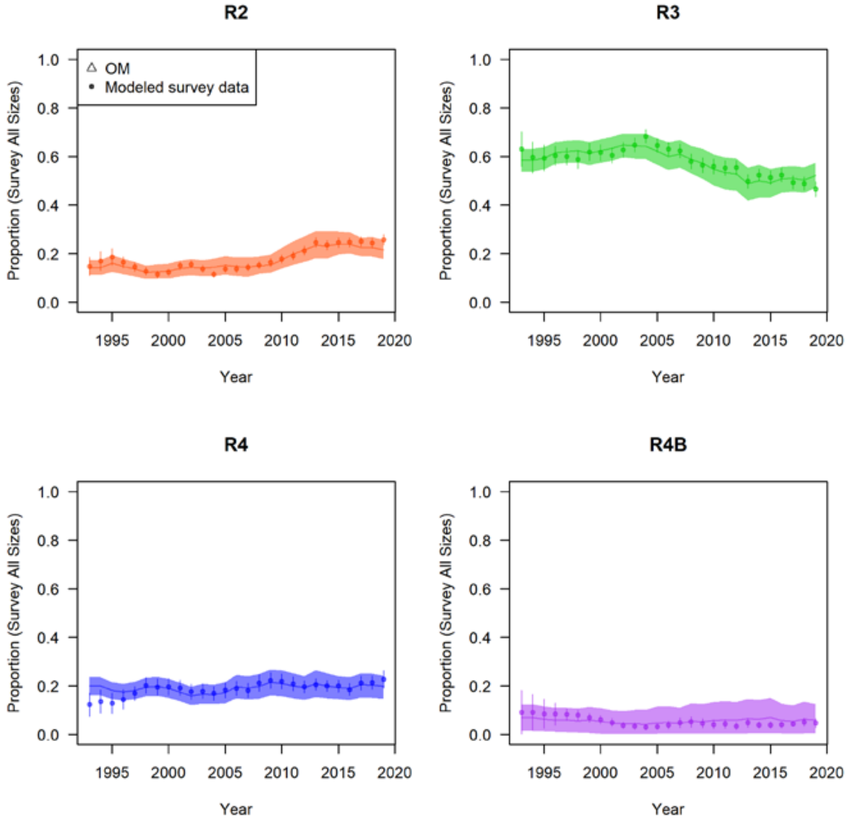

Figure 8: Stock distribution determined from FISS observations (points) and from the OM with variability (shaded areas).

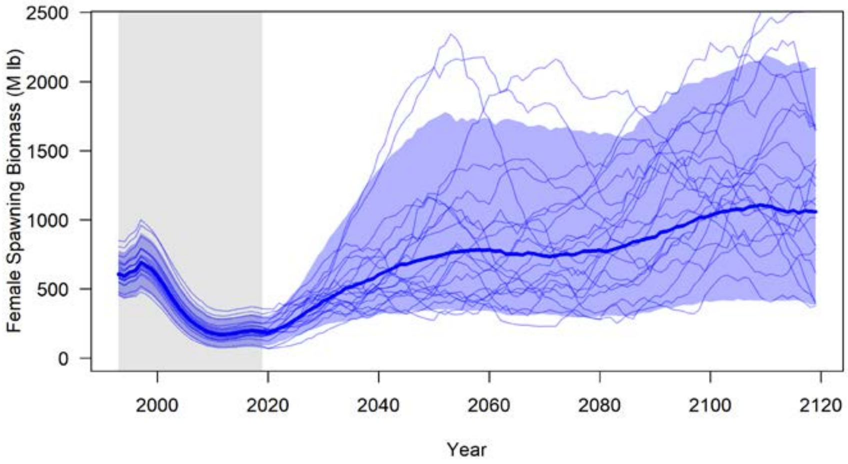

Figure 9: The 90% credible interval from six-hundred simulated projections for 100 years without fishing mortality. The blue line is the median and the pink shaded area show the interval between the 5th and 95th percentiles. The light shaded grey area between 1993 and 2019 is the historical period, and 2020 has fixed fishing mortality based on the already defined catch limits for 2020. The grey lines are the first 20 individual trajectories.

2.3 Management Procedure

The management procedure consists of three elements. Monitoring (data generation) is the code that simulates the data from the operating model. The data generation routine attempts to simulate the data collection and sampling process, and introduces in the data variability, bias, and any other desired property. The data so generated are then used by the estimation model. The Estimation Model (EM) is analogous to the stock assessment and simulates estimation error in the process. 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 are in general 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 1) to produce the mortality limit for that year.

2.3.1 Uncertainty in the management procedure

The major source of uncertainty in the management procedure is from 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. These simulated data are then fed into the estimation model to approximate the current stock assessment ensemble or used in the management procedure (e.g., stock distribution).

The observation model generates the data for the EMs during projections from the OM with error. In particular, deviates to the absolute index of abundance and the stock distribution are generated by region from a lognormal distribution with standard deviation equal to the average standard error by region from the last 5 years. Age composition data are simulated using a Dirichlet distribution. The nominal sample size is 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 generated using an average fixed proportion of the sector mortality. The resulting sample size values are bounded between a minimum and a maximum, which varies between sectors: these limits have been chosen based on the historical sample size values and help both to stabilize the EM, as well as to avoid unrealistic distribution in the simulated age composition.

Three methods are available for simulating the estimation process. First, there is the option of no estimation model where the data are produced without error and the estimation model returns the population and predicted mortality values determined exactly from the OM. The second method simulates the estimation error (autocorrelated estimation error about the true population values) as was done in the coastwide MSE. This method is simple and less prone to errors during simulation that some other methods may experience. The third method is to use a stock assessment model, such as stock synthesis and enter the generated data. The model chosen to emulate the current stock assessment ensemble is the long coastwide model in stock synthesis, which has been appropriately simplified to reduce run time. Using actual stock assessment models may better characterize the estimation variability than simpler approaches.

The values generated from the estimation model are used in the application of the harvest rule to determine mortality limits by IPHC Regulatory Area. The simulated application of this rule will therefore include uncertainty in the status, the size of the population, stock distribution, etc., all of which will be propagated into management actions.

2.3.1.1 No estimation error

The stock status, total mortality given the input SPR, the stock distribution, and any other quantities needed for the MP are known exactly for this option. This is useful to identify variability that is due to estimation.

2.3.1.2 Simulated estimation error

For this method, error is added to the stock status and total mortality given the input SPR that are used in the MP by adding deviates to each that are sampled from a bivariate normal distribution with a 15% coefficient of variation on each and a correlation of 0.5. Additionally, an autocorrelation of 0.4 is used with the deviate from the previous year. This is the same method that was used in the coastwide MSE as described in IPHC-2018-MSAB012-07 Rev_1. Stock distribution is determined from survey data generated with random error similar to error estimates from the current survey time-series.

2.3.1.3 Estimation models using stock synthesis

Two approaches were used to speed up the long coastwide estimation model for use in the MSE simulations: 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. Only the beginning of the CPUE time series was maintained, removing all subsequent years starting from 1994. Additionally, the model was started in 1935 instead of 1888.

The major change to the data is the use of an absolute index of abundance to replace the NPUE from the survey. The index is generated with error from the numbers at age and the survey selectivity at age for the whole time series. The catchability is fixed to 1.

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. 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 or 20 years (depending on the parameter) 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 criterion was set to 0.1, the Hessian was not estimated (therefore uncertainty in the estimates is not 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.

For each OM, data for the historical period were generated and input files for the long coastwide assessment models were created, so to have each set of estimation models consistent with the historical period of the correspondent OM. The initial parameter files used are the same across all simulations.

Performance of the stock synthesis estimation model

Ten simulations with 60 years projections were run to evaluate the performance of the long coastwide stock synthesis assessment as estimation model with different OMs. The stock synthesis estimation model closely matches the stock status and the fishing intensity from the operating model (Figure 10).

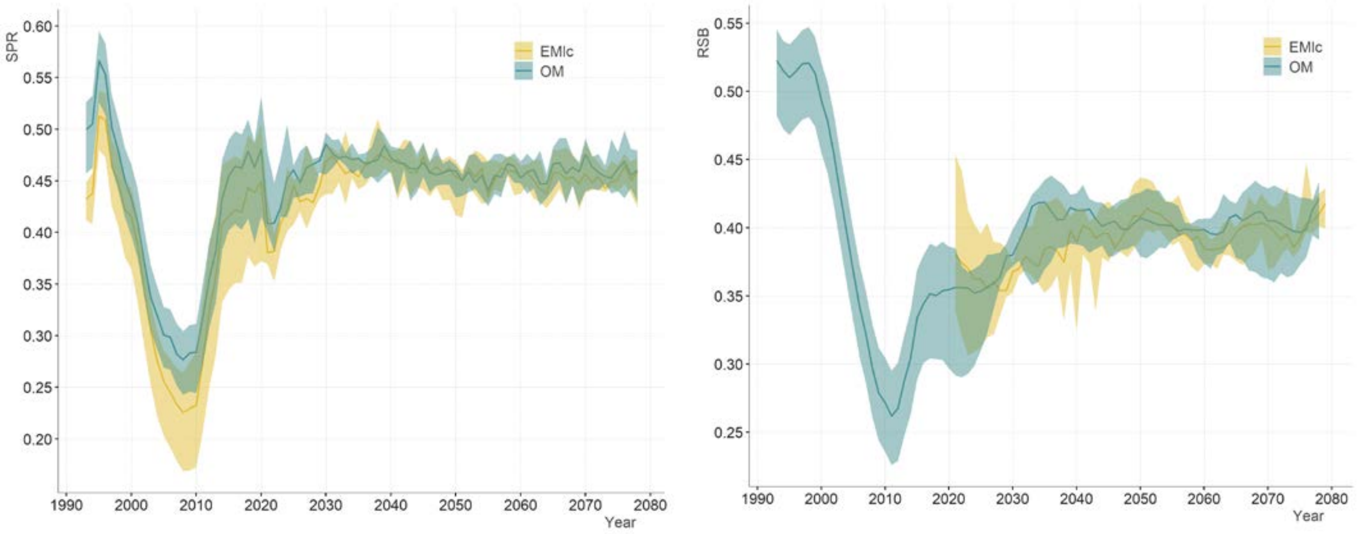

Figure 10: SPR and RSB as estimated by the OM (blue) and the long coastwide estimation model (yellow) for 10 simulations.

2.3.2 Allocating simulated total mortality to sectors

The outputs of the management procedure are TCEY limits for each IPHC Regulatory Area, which then need to be allocated to the different sectors specific to the IPHC Regulatory Area. See Table 2 for a complete list of the fishing sectors by IPHC Regulatory Area.

There are two parts to the allocation procedure: the calculation of the upcoming mortality limits by sector, and the calculation of the realized mortality by sector. The calculation of mortality limits is necessary because some sector's mortality limits are determined from the limits for other sectors. In the current framework, the calculation of the realized mortality differs from the calculation of the mortality limits for the non-directed discard, directed discard, subsistence, and unguided recreational mortalities. Mortality limits and realized mortality for the recreational and directed commercial sectors are assumed to be equal (i.e., no implementation error for these sectors).

The allocation procedure begins by subtracting the non-directed commercial O26 discard mortality by IPHC Regulatory Area from the corresponding IPHC Regulatory Area TCEY. The remainder is referred to as the directed TCEY for convenience (it is not used as a management quantity). The directed TCEY is then allocated to directed fishery sectors. Each IPHC Regulatory Area has a unique catch-sharing plan (CSP) or allocation procedure, and these CSPs were matched as closely as possible. When the TCEY for an IPHC Regulatory Area is low, the CSP may deteriorate and alternative decisions may be necessary. At low TCEY, it is assumed that the sum of the directed non-FCEY components does not exceed the directed TCEY: this is evaluated removing sequentially the non-directed discard mortality, the subsistence and unguided recreational (where available) from the TCEY. If any of these mortalities exceed the remaining TCEY, the FCEY components are set to zero.

Non-directed commercial discard mortality: the U26 and O26 components of the non-directed discard mortality limit is calculated from the previous year's non-directed discard mortality for each IPHC Regulatory Area. However, the realized non-directed discard mortality is determined from a linear relationship between the non-directed discard mortality by region and the total biomass in that region. Given changes in non-directed commercial discard mortality in recent years the fit was forced through the last observed year (2019). The realized non-directed discard mortality was then randomly drawn from the value determined from total biomass by region using a log normal distribution with a 20% CV (Figure 11). The non-directed commercial discard mortality by region is then distributed to IPHC Regulatory Area using the proportion of non-directed commercial discard mortality recently observed in each IPHC Regulatory Area.

Directed commercial discard mortality: directed commercial discard mortality limits are calculated using the ratio of directed discard mortality to directed commercial mortality from the previous year. The realized directed discard mortality is modelled as a function of the directed commercial plus directed discard mortality and the weight at age 8 for a male Pacific halibut. The resulting proportion of directed discard mortality relative to different values of the commercial plus directed discard mortality is shown in Figure 12. A minimum of 0.05% of directed discard mortality over commercial plus directed discard mortality is applied.

Subsistence: subsistence mortality limits are set equal to the values observed in the previous year, except for IPHC Regulatory Area 2A, for which the subsistence value is set to 30,000 pounds (13.6 t). The realized subsistence mortality is randomly drawn from a lognormal distribution with a median equal to the limit subsistence mortality and a CV of 15%. The coastwide subsistence is then compared to the coastwide TCEY: if the allocation to the subsistence sector is higher than half of the overall TCEY, then the subsistence mortality in each regulatory area is adjusted so that the coastwide value will not exceed 50% of the coastwide TCEY.

Unguided recreational mortality: unguided recreational mortality is relevant only for IPHC Regulatory Areas 2C and 3A and it is randomly drawn from a lognormal distribution with a median equal to an average historical value (1.257 Mlb or 570 t for 2C and 1.579 Mlb or 716 t for 3A) and a 5% CV.

Recreational mortality: recreational mortality follows the catch sharing plans (CSPs) for IPHC Regulatory Areas in Region 2 and IPHC Regulatory Area 3A, noting that guided recreational mortality limits are only under the CSP in IPHC Regulatory Areas 2C and 3A and the total recreational mortality is the sum of guided and unguided. In IPHC Regulatory Areas 3B, 4A, 4B, and 4CDE, recreational mortality is included with subsistence because almost negligible.

Commercial mortality: is the remainder of the total mortality after subtracting all other sources of mortality.

Figure 13 and Figure 14 illustrate the results of the allocation procedure for each IPHC Regulatory Area when non-directed commercial discard mortality and unguided recreational are held constant at an average value. The recreational and subsistence allocations for IPHC

Regulatory Areas 4A and 4CDE are fixed at low values and aggregated to Biological Region in the OM. For this reason, these two sectors are not shown in Figure 14.

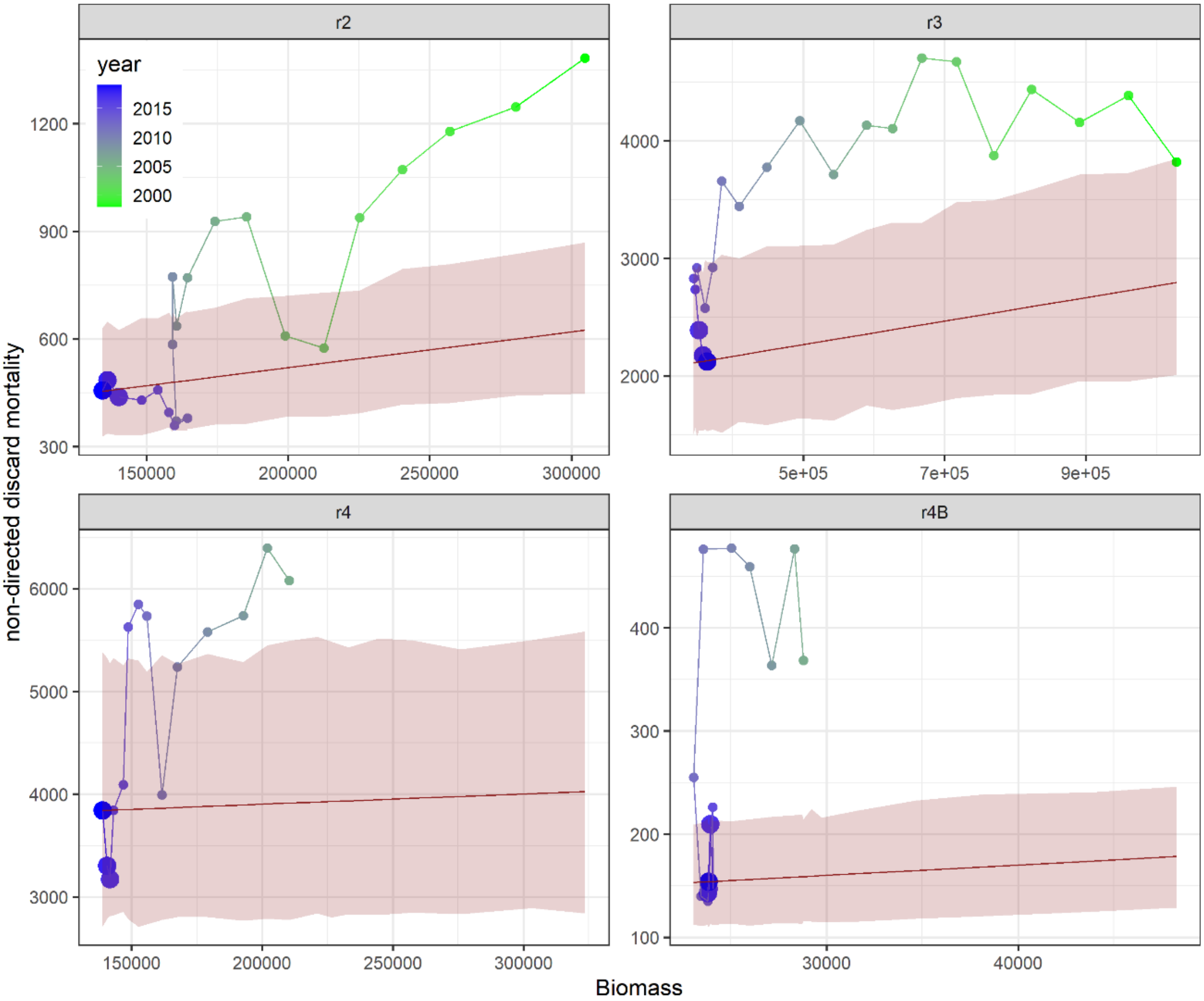

Figure 11: Non-directed commercial discard mortality plotted against total biomass from the conditioned multi-region OM. The colors in the points represent the sequence of time from 1998 to 2019. The years 2017–2019 are represented by larger dots. The red line represents the linear relationship used for predicting the non-directed discard mortality from the biomass. The shaded red area around it represents the 0.05 and 0.95 quantiles of the non-directed discard mortality simulated from a log-normal distribution with a 20% CV.

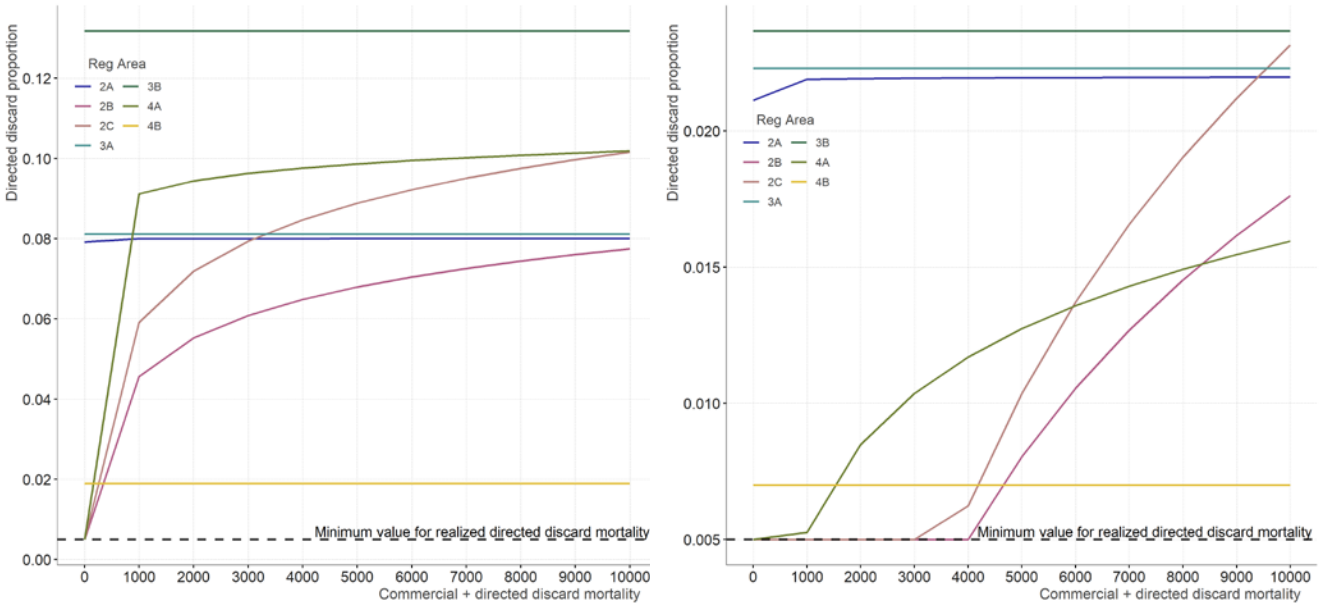

Figure 12: Proportion of directed discard mortality by IPHC Regulatory Area relative to different values of the commercial plus directed discard mortality with a male weight at age 8 equal to 4 lb (left) and 8 lb (right). The dashed line shows the 0.5% minimum.

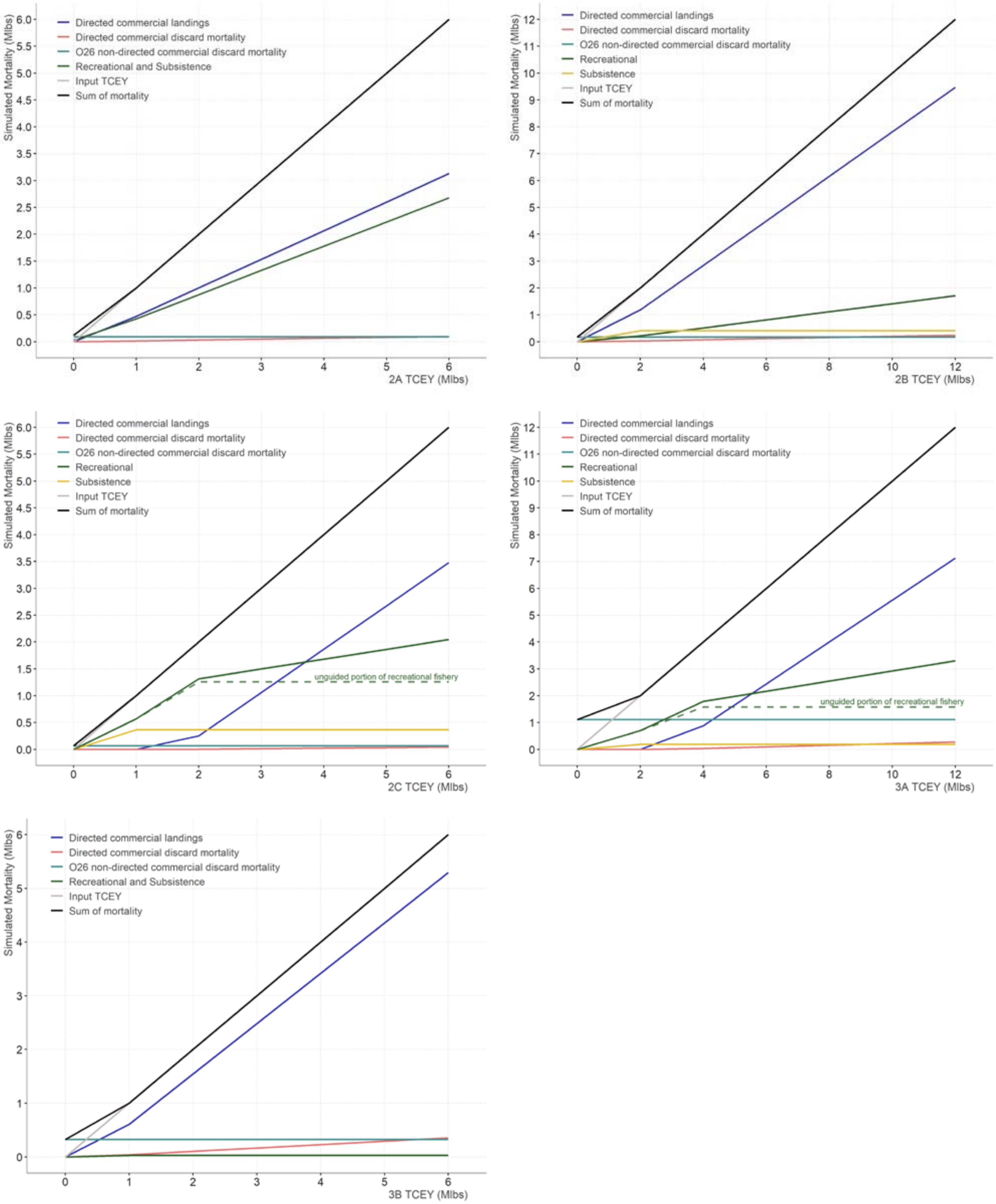

Figure 13: Allocation of the TCEY to sectors for IPHC Regulatory Areas 2A (top left) to 3B (bottom left) when O26 non-directed commercial discard mortality and unguided recreational are is assumed constant at average values. The input TCEY provided to the allocation function is shown in light gray, while the sum of mortalities after allocation is shown in black.

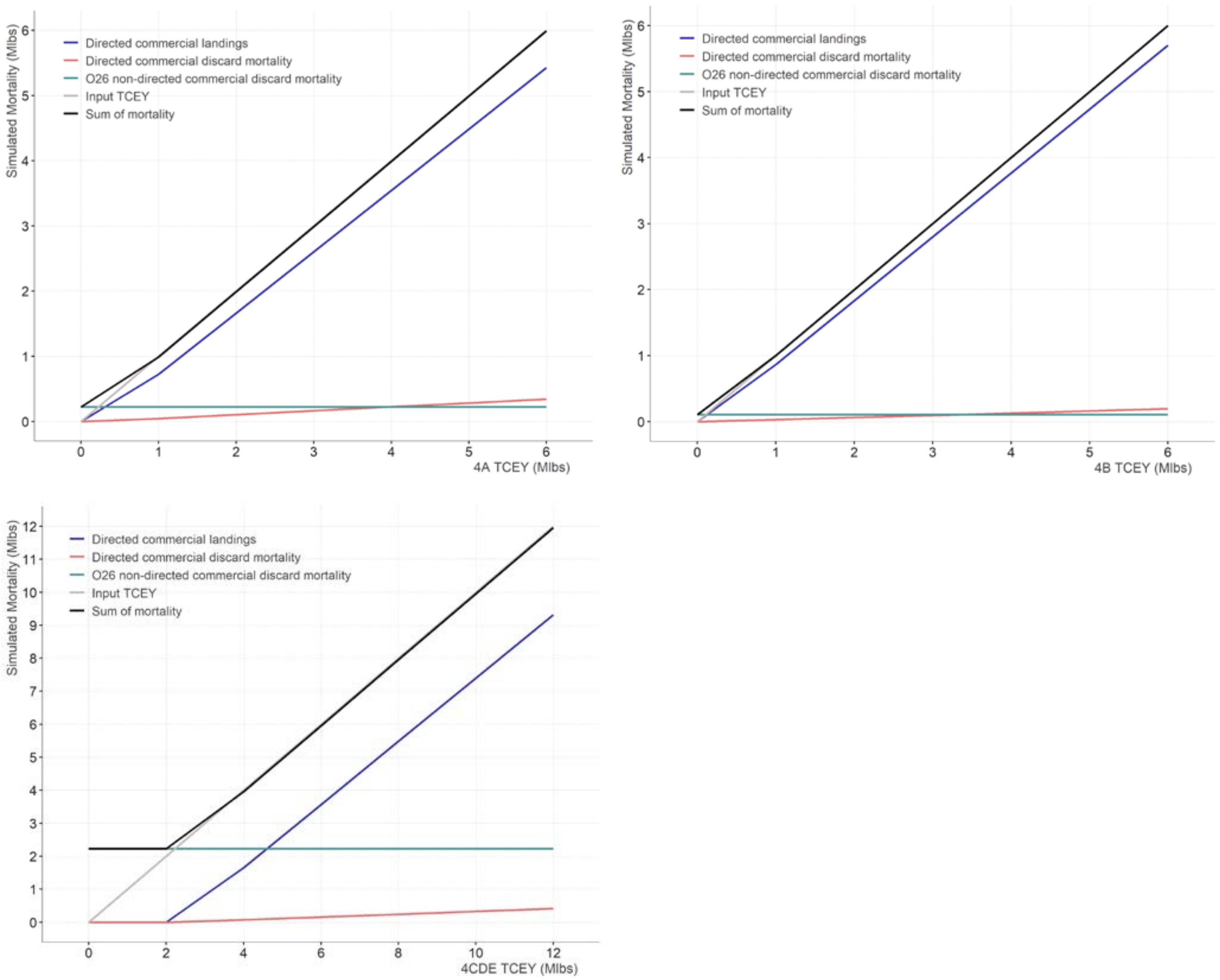

Figure 14: Allocation of the TCEY to sectors for IPHC Regulatory Areas 4A (top left), 4B (top right), and 4CDE (lower left) when O26 non-directed commercial discard mortality is assumed constant at an average value. The input TCEY provided to the allocation function is shown in light gray, while the sum of mortalities after allocation is shown in black.

3 RECOMMENDATIONS

That the MSAB:

a) **NOTE** paper IPHC-2020-MSAB016-08 which provides a description of the IPHC MSE framework, a description of the specifications of the multi-area operating model, and a brief overview of the implementation of management procedures.

b) **RECOMMEND** alternative specifications and additional features needed to evaluate management procedures related to coastwide scale and distribution of the TCEY, also **NOTING** document IPHC-2020-MSAB016-INF01.

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5 APPENDICES

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