An evaluation of dynamic reference points for Pacific halibut, *Hippoglossus stenolepis*

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PURPOSE

To provide an analysis and comparison of dynamic equilibrium reference point estimates for Pacific halibut using three different methods. Reference points include unfished spawning biomass, maximum sustainable yield (MSY), relative spawning biomass at MSY (RSB_{MSY}), and the fishing intensity (F_{SPR}) that results in MSY (SPR_{MSY}). These reference point estimates may provide a basis for defining management objectives being considered in the IPHC's ongoing Management Strategy Evaluation (MSE).

1 INTRODUCTION

The development of an objective defined around a relative spawning biomass target (i.e. a level to fluctuate around with a 50% probability to be above or below) was discussed extensively at MSAB013. Noting that the current IPHC harvest strategy policy suggests using a proxy for Maximum Economic Yield (MEY), which is related to Maximum Sustainable Yield (MSY), much of the discussion focused around these quantities and what appropriate proxies may be. The need to maximize the economic benefit has been widely recognized, however, the estimation of MEY and related spawning biomass and fishing mortality quantities (SB_{MEY} and F_{MEY}) is still quite challenging and requires a deep understanding of the economic variables relevant to the fishery. In absence of this information and of a bio-economic model of the fishery, a proxy for MEY may be obtained from MSY. For example, the Australian government's harvest strategy policy uses the relationship: $SB_{MEY} = 1.2 \times SB_{MSY}$ (Rayns 2007), and Pascoe et al. (2014) suggested that $SB_{MEY} = 1.45 \times SB_{MSY}$ for data-poor single-species fisheries, where SB_{MSY} refers to the equilibrium spawning biomass that would result when fishing at MSY.

Reference points are not static quantities but change over time depending on productivity regimes and natural variation in a population. The difference between static reference points and their dynamic counterpart can be substantial (Berger 2019) and failing to consider it might influence the perception on the status of a particular stock. Berger (2019) observed that the dynamic B_0 approach performs better when clear trends in stock productivity have been observed and management objectives focus on current reproductive capacity, such as the case of Pacific halibut.

Currently, for Pacific halibut (*Hippoglossus stenolepis*), there is no estimate of SB_{MSY}. Given natural variability in the biomass of Pacific halibut, mostly due to productivity regimes and annual variability in weight-at-age and recruitment, and potential variability in fishery selectivity-at-age, determining MSY related reference points has been challenging (Clark and Hare 2006). Instead 'common sense' limits have been used that were based on historical observed minimum biomass levels for the stock. Preliminary analyses based on recent stock assessments and equilibrium models has suggested that SB_{MSY} may be lower than 30% of unfished spawning biomass. More investigation is needed to identify a robust range of possible estimates to guide the development of a proxy for MSY, and potentially MEY, in light of the dynamic nature of the stock and fisheries, as well as uncertainty in stock-recruit parameters.

Fisheries management has used the concept of maximum sustainable yield for many decades (e.g., Schaefer (1954)) as well as other equilibrium reference points. It has also been recognized that there are risks associated with managing to MSY (Larkin 1977) and proxies may be useful to mitigate those risks (Gabriel and Mace 1999). For example the Pacific Fishery Management Council (PFMC) uses a proxy SB_{MSY} target for flatfish of 25% of unfished spawning biomass and a proxy SB_{MSY} of 40% for other groundfish species (PFMC 2016). The North Pacific Fishery Management Council (NPFMC) Bering Sea/Aleutian Island Fishery Management plan (NPFMC 2018) specifies 30% as a proxy for SB_{MSY} when SB_{MSY} cannot be adequately estimated.

Reference points for Pacific halibut, such as unfished equilibrium stock size and MSY, are likely to change dramatically over time because of changes in productivity and size-at-age. The IPHC MSE work (IPHC-2018-MSAB012-07) and more recently the stock assessment (IPHC-2019-AM095-09) have been using dynamic SB_0 to determine relative stock size, which is calculated using the estimated population parameters, cohort strengths, and stock recruitment function contributing to the spawning biomass in that year, but without fishing mortality (Methot and Wetzel 2013). Dividing the spawning biomass by the dynamic SB_0 is a measure of the effect of fishing on the spawning biomass in that year and removes the effect of the non-fishing influences on the population, such as environmental effects on average recruitment, changes in size-at-age, and recent cohort sizes. Dynamic relative spawning biomass has been used in some tuna assessments (e.g., Harley et al. (2014).

A slightly different dynamic calculation is used to determine MSY-based reference points. MSY is a long-term equilibrium concept, thus we use the term dynamic equilibrium reference point (e.g., dynamic equilibrium SB_0). The difference between dynamic equilibrium SB_0 and dynamic SB_0 is that the dynamic equilibrium SB_0 uses the equilibrium recruitment (R_0, adjusted for the relative regime) instead of accounting for estimated recent cohort strengths. The dynamic equilibrium reference points reflect the average conditions of the stock in a particular year if the stock parameters were to remain the same in perpetuity. Being dynamic, the reference points will change over time.

Three approaches were used to investigate dynamic equilibrium reference points for Pacific halibut. The first methodology used an equilibrium model with variability and sensitivities to size-at-age and unfished recruitment. The second approach used the 2018 assessment for Pacific halibut (IPHC-2019-AM095-09) and calculated the dynamic equilibrium reference points for all years in each model from the ensemble up to 2018. The third method used the coastwide MSE operating model (IPHC-2018-MSAB012-07) to determine dynamic equilibrium reference points for the simulated population given various assumptions about recruitment regime, size-at-age, and changes in selectivity for the commercial Pacific halibut fleet. These analyses will provide a range of possible values for the various MSY-based reference points given different initial conditions and assumptions. Furthermore, a comparison of these results from each method is provided to determine their utility for the MSE process and definition of management objectives.

2 METHODS

Four reference points were calculated using three different approaches: dynamic equilibrium unfished spawning biomass (SB_0), dynamic equilibrium maximum sustainable yield (MSY), relative dynamic equilibrium MSY spawning biomass (RSB_{MSY}), and dynamic equilibrium fishing intensity measured using spawning potential ratio (SPR_{MSY}, which is a measure of the fishing intensity describing the effect on the lifetime spawning output per recruit). The approaches used to investigate these dynamic reference points are briefly summarized below. More detailed information on each method is supplied in Appendices I-III.

1. A **deterministic equilibrium model** was built to forward project the population using parameter estimates from the Long-Coastwide Stock Synthesis assessment model from the 2018 Pacific halibut stock assessment (IPHC-2019-AM095-09).
2. The **2018 Pacific halibut stock assessment** (IPHC-2019-AM095-09) was used to test how the dynamic equilibrium reference points have changed through time retrospectively.
3. The coastwide **MSE operating model (OM;** IPHC-2018-MSAB012-07) was used to estimate the dynamic equilibrium reference points given simulated variability determined from parameter uncertainty, process variation in selectivity, and structural uncertainty from two models (a short-time series of data and a long time-series of data).

In all three methodologies, variability in the dynamic equilibrium reference points was examined by considering environmental regimes (either a high or low unfished average recruitment), size-at-age (a dynamic range of weight-at-age or scenarios for low, medium, and high weight-at-age), variability in selectivity of the commercial fishery, variability in steepness, and variability in natural mortality. Additional sources of variation were used in the MSE OM approach, but the five sources listed above are likely the largest sources of variability in the reference points. These five sources of variability are described in the following paragraphs.

Recruitment regime: the two “long time-series” models in the 2018 IPHC stock assessment (IPHC-2019-AM095-09) estimated a link between the Pacific Decadal Oscillation (PDO, Mantua et al. (1997)) and average unfished equilibrium recruitment (R_0). Previous analyses (Clark and Hare 2002, Stewart and Martell 2016) have shown that a positive PDO phase is correlated with enhanced productivity, while productivity decreases in negative PDO phases. The Pacific halibut stock assessment simplifies the process by estimating an unfished average recruitment (R_0) for two states, low or high. Estimates of R_0 from the Long Coastwide model are 56.033 million in the low state and 80.368 million in the high state. These values were used for unfished equilibrium recruitment in these analyses. The Short Coastwide model did not estimate an environmental link and recruitment was estimated freely, thus R0 was not a meaningful parameter for that model. However, the estimated average recruitment over the period 1987–2012 was approximately 38 million.

Weight-at-age: weight-at-age has varied considerably for Pacific halibut since the early 1900s. In particular, there is a clear pattern of increasing fish size from the 1930s through the 1970s, followed by a subsequent decline to the present, with marked differences among regulatory areas (Clark and Hare 2002, 2006, Stewart 2017). This trend is a strong driver of the stock dynamic as perceived by the assessment models in recent years (IPHC-2019-AM095-09). To examine how changes in weight at age would affect the reference point estimation, different weight at age scenarios were calculated from the weight-at-age matrix currently used in the Pacific halibut stock assessment. Low, medium, and high states were determined by calculating the 15^{th}, 50^{th}, and 85^{th} percentiles of the historical weight-at-age (1935–2017) for each age, running a loess smoother through the specific quantile-at-ages, and then making sure it increases monotonically over age by predicting weight (from the loess model) for any ages that had a weight less than the weight at a younger age (which may occur in the actual annual estimates, but would not make sense in the long-term use in an equilibrium model or for parameterizing the OM). Figure 1 shows the low, medium, and high weight-at-age states for females and males. When weight-at-age was not a specific scenario in the MSE OM, variability was modelled as a random walk with year and cohort effects (see IPHC-2018-MSAB012-07).

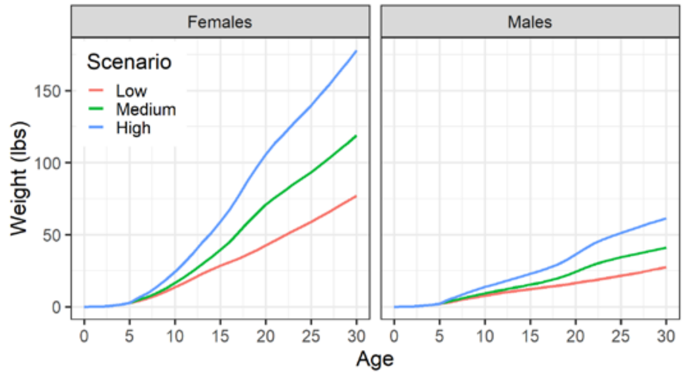

Figure 1. Low, medium and high weight at age states for females (left) and males (right).

Selectivity: variations in selectivity can be the result of changes in fishing practices as well as changes in the structure of the population, of the fishery or of fish movement, which may affect the availability of certain age classes. The effect of changes in selectivity on reference point estimates was tested using different assumptions, either in the form of specifying different selectivity curves (equilibrium model) or by simulating changes in selectivity parameters (and thus selectivity curves) with a link to weight-at-age (MSE model). In the equilibrium model, the selectivity curves used for the commercial fleet were selected from the results of the Long Coastwide model with selectivity-at-age from the years 1960 and 2001 representing two scenarios (Figure 2). The selectivity-at-age from 1960 was skewed towards younger ages for both sexes, while the selectivity-at-age from 2001 was skewed towards older ages. These selectivity curves represent the landed fish and do not include directed fishery discard mortality. Selectivity for the non-directed discard mortality fleet was also determined from the Long Coastwide model and is equal between sexes and time-periods (Figure 2).

Steepness and natural mortality: The data used in stock assessment models quite often have little or no information about steepness and natural mortality and it is common practice to assume fixed values for both parameters (Mangel et al. 2013). However, steepness and natural mortality share a deep connection with reference points and different assumptions can lead to very different reference points estimates. Steepness values of 0.5, 0.75, and 0.9 were examined in the equilibrium model, and a value of 0.75 was used in the 2018 stock assessment model (as has been assumed in recent stock assessments of Pacific halibut). The MSE OM integrated uncertainty in steepness by drawing from a distribution centered on 0.75 (see IPHC-2018-MSAB012-07).

Female natural mortality was fixed at 0.15 in the two Short models of the Pacific halibut stock assessment and it was estimated in the two Long models. Male natural mortality was estimated in all models in the Pacific halibut stock assessment. Variability in this parameter was examined using two natural mortality scenarios (high and low M) in the equilibrium model determined from the Long and Short coastwide models: females = 0.218 and males = 0.172 from the Long model and females=0.15 and males = 0.138 from the Short model. The same estimated values were used in the 2018 stock assessment method, and a range of values from the estimated uncertainty distribution were used in the MSE OM method (IPHC-2018-MSAB012-07).

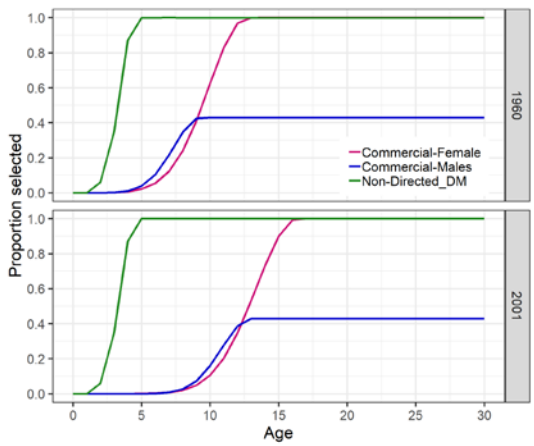

Figure 2. Selectivity-at-age scenarios used for the calculation of MSY with the equilibrium model. Top graph: 1960 selectivity for the directed commercial fleet (males and females) and the non-directed discard mortality fleet (same for both sexes). Bottom graph: 2001 selectivity for the directed commercial fleet (males and females) and the non-directed discard mortality fleet (same for both sexes).

2.1 EQUILIBRIUM MODEL

The equilibrium model approach used a two-sex equilibrium model designed to have flexibility in specification to examine the effects of various scenarios and parameterizations on reference points (Appendix I). Two fishing fleets were considered in the model: directed commercial (without discard mortality) and non-directed discard mortality (bycatch). Values of fishing mortality from 0 to 0.8 at a 0.001 interval were used, and fishing mortality was partitioned between the two fleets with a specified percentage of 80% to the commercial fleet and 20% to the non-directed discard mortality fleet. Parameterization (i.e., selectivity) was derived from the Long coastwide stock assessment model, as noted above. The model projected forward 200 years with deterministic recruitment and used the last year (assumed to be equilibrium) of the projection to determine the reference points.

As described above, a grid of scenarios included different selectivity curves (1960 and 2001), weight-at-age (low, medium, and high), steepness (0.5, 0.75, 0.9), environmental regimes (low or high), and natural mortality (high, low) to characterize the potential variability in the reference points. The two long-time-series assessment models estimated an unfished average recruitment (R_0) for two states, low or high. Here, we used R0 estimates from the Long Coastwide model, which are equal to 56.033 million in the low state and 80.368 million in the high state. When lower values of natural mortality (M) from the Short Coastwide model were used, we used also the R_0 estimate from this same model, which corresponds to the high regime condition. The R_0 for the low regime was calculated using the Long Coastwide proportion between high and low R_0, and applying that to the Short Coastwide R_0 estimate. The resulting values for R_0 are 12.180 million for the high regime and 8.492 million for the low regime. However, these values of R_0 are not on the correct scale since the Short Coastwide model estimated recruitment freely and average recruitment over the period 1987–2012 was approximately 38 million. Therefore, the scale of SB_0 and MSY will be low, but the ratios RSB_{MSY} and SPR_{MSY} are appropriate.

Additionally, one run with the same weight-at-age (medium), selectivity (2001), and natural mortality (0.218) for males and females was carried out to evaluate the impact of the sexual traits on reference point estimates.

2.2 2018 ASSESSMENT MODEL

The four assessment models developed for Pacific halibut (IPHC-2019-AM095-09) were used independently to estimate reference points retrospectively. The routine is detailed in Appendix II. Starting from the final year in the stock assessment (2018), the stock synthesis platform was used without estimation (fixing parameters at the values from the assessment) to recalculate dynamic equilibrium reference points for each year retrospectively back to the start year of the model. The 'short' models started in 1996 and the 'long' models started in 1888, although the model parameters were constant from 1888 to 1935, including weight-at-age and environmental regime (at the high state).

Weight-at-age and selectivity for the associated year, and R_0 from the current regime (low or high) in the associated year when an environmental link was estimated (Long model) were used to estimate a time-series of dynamic equilibrium reference points for all years included in each model up to 2018. With recruitment estimated freely in the Short models, the scale of biomass and mortality is not correct in the calculations. However, the ratios RSB_{MSY} and SPR_{MSY} are correct. Uncertainty was not estimated because these parameters are not estimated as part of the optimization process but are calculated *post hoc* using fixed values.

2.3 MSE OPERATING MODEL

A similar procedure as with the stock assessment was used to calculate dynamic equilibrium reference points using the MSE operating model (IPHC-2018-MSAB012-07), except that it started at the final year of a 100-year simulation and worked backwards for 50 years. Two models from the 2018 stock assessment (Short and Long Coastwide models, IPHC-2019-AM095-09) each simulated five-hundred different trajectories with different parameters determined from the estimated uncertainty in the stock assessment (see IPHC-2018-MSAB012-07). The estimates from all trajectories were used to characterize the uncertainty in the dynamic equilibrium reference points. The variability in the reference points due to the environmental regime was investigated by fixing the regime at either a high or a low value. Variability in selectivity was incorporated by simulating changes in selectivity parameters with a link to weight-at-age (see IPHC-2018-MSAB012-07). Variability in weight-at-age was investigated by simulating a random walk for weight-at-age (IPHC-2018-MSAB012-07).

Reference points were integrated over the structural uncertainty of the two models, the parameter uncertainty introduced by the five-hundred simulated trajectories, the high and low states of the environmental regime, simulated changes in selectivity, and the simulated variability in weight-at-age by combining the estimated reference points from the final year of the 2000 trajectories from the two models and two environmental regimes. Additionally, three scenarios of weight-at-age (low, medium, and high), as with the equilibrium method, were used to examine the specific effect of weight-at-age on the dynamic equilibrium reference points. The Short model did not estimate an environmental linkage, thus the results for low and high regimes in this model are the same, other than simulation error, but the structure of 500 simulations of low and high regime from the Short model was retained so that the models were equally weighted in the integration of the results. The Short model used the incorrect value for unfished equilibrium recruitment (R0) thus the scale of biomass and mortality are incorrect and not reported. However, the ratios RSB_{MSY} and SPR_{MSY} are correct.

3 RESULTS

3.1 EQUILIBRIUM MODEL

Using the equilibrium model, SB_0 and MSY varied considerably across scenarios with a higher weight, higher R_0, and higher M producing larger values of SB_0 and MSY (Figure 3). The relative spawning biomass at MSY (RSB_{MSY}) and the spawning potential ratio at MSY (SPR_{MSY}) showed less variability across scenarios with steepness being the most influential parameter (Figure 3). Within each steepness scenario, selectivity was the largest factor for differences in RSB_{MSY} and SPR_{MSY}. Low values of R_0 and weight at age, and higher selectivity for younger ages (selectivity from 1960) resulted in the lowest estimated RSB_{MSY} and SPR_{MSY} for a given steepness, but increased as steepness lowered (when the dependence between recruitment strength and stock biomass is higher, a lower exploitation rate will maximise yield). The estimates of RSB_{MSY} ranged from 33–37% with a steepness of 0.5, 22–28% with a steepness of 0.75, and 15–23% with a steepness of 0.9. The estimates of SPR_{MSY} ranged from 50–52%, 29–34%, and 17–25% with steepness values of 0.5, 0.75, and 0.9, respectively.

The two recruitment scenarios examined produced similar estimates of RSB_{MSY} and SPR_{MSY} because the shape of the stock-recruitment curve doesn’t change, but it is only re-scaled to higher levels. The scenario with no differences between male and female M, weight-at-age and selectivity resulted in the highest values of RSB_{MSY} and SPR_{MSY} (lower exploitation) within the same steepness scenario.

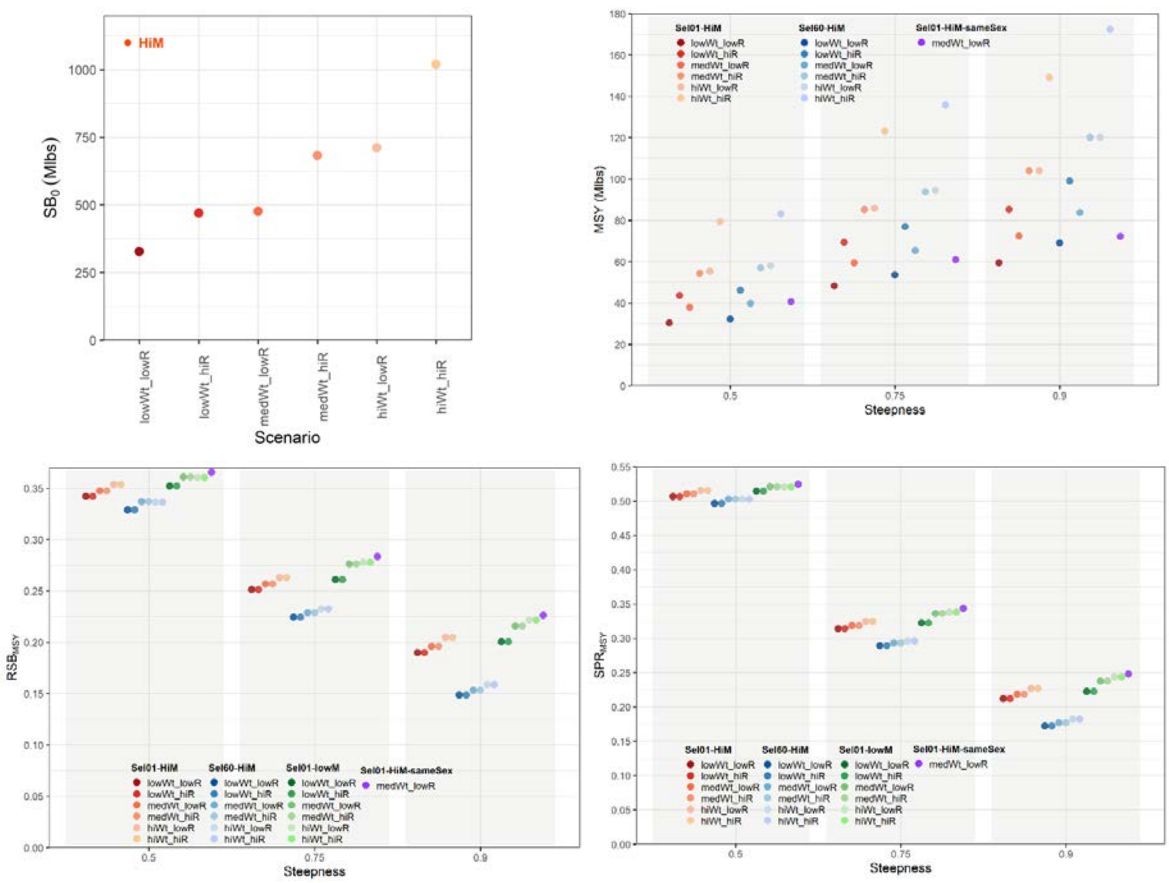

Figure 3: Estimated dynamic equilibrium reference points from the equilibrium model. SB_0 and MSY for the Short models are not shown due to a misspecification of the scale.

Table 1. MSY reference points (RSB_{MSY} and SPR_{MSY}) from the deterministic equilibrium model for all scenarios, i.e. three steepness values, two natural mortality values, two selectivity specifications, two recruitment regimes, and three weight-at-age scenarios.

Steepness	0.5																		
Model	High M												Low M						High M*
Selectivity	2001						1960						2001						2001*
Weight-at-age	Low		Med		High		Low		Med		High		Low		Med		High		Med*
Regime	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
RSB_{MSY}	34%	34%	35%	35%	35%	35%	33%	33%	34%	34%	34%	34%	35%	35%	36%	36%	36%	36%	37%
SPR_{MSY}	51%	51%	51%	51%	52%	52%	50%	50%	50%	50%	50%	50%	51%	51%	52%	52%	52%	52%	52%

Steepness	0.75																		
Model	High M												Low M						High M*
Selectivity	2001						1960						2001						2001*
Weight-at-age	Low		Med		High		Low		Med		High		Low		Med		High		Med*
Regime	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
RSB_{MSY}	25%	25%	26%	26%	26%	26%	22%	22%	23%	23%	23%	23%	26%	26%	28%	28%	28%	28%	28%
SPR_{MSY}	31%	31%	32%	32%	32%	32%	29%	29%	29%	29%	30%	30%	32%	32%	34%	34%	34%	34%	34%

Steepness	0.9																		
Model	High M												Low M						High M*
Selectivity	2001						1960						2001						2001*
Weight-at-age	Low		Med		High		Low		Med		High		Low		Med		High		Med*
Regime	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
RSB_{MSY}	19%	19%	20%	20%	20%	20%	15%	15%	15%	15%	16%	16%	20%	20%	22%	22%	22%	22%	23%
SPR_{MSY}	21%	21%	22%	22%	23%	23%	17%	17%	18%	18%	18%	18%	22%	22%	24%	24%	24%	24%	25%

*no sex difference in natural mortality, selectivity, or weight-at-age

3.2 ASSESSMENT MODEL

The retrospective estimates of the four dynamic equilibrium reference points from the assessment model are shown in Figure 4 along with the environmental regime assumed for various time-periods. The Long models show a clear change in the scale of SB_0 and MSY associated with the environmental regime (lower values in low states) and trends within each regime which is likely due to changes in weight-at-age, which occur slowly and systematically over time. The relative-spawning biomass at MSY (RSB_{MSY}) and the SPR at MSY (SPR_{MSY}) are much more consistent across time and models.

The minimum and maximum reference points over the retrospective time-series and for each model and environmental regime shown in Table 2 and Figure 5 further illustrate the consistency in RSB_{MSY} and SPR_{MSY}. The reference point RSB_{MSY} ranges from 22% to 27% across all models and environmental regimes, and SPR_{MSY} is slightly higher, as expected, ranging from 29% to 33%

Table 2. Minimum and maximum estimated dynamic equilibrium reference points over the entire time-series from the recent stock assessment model (IPHC-2019-AM095-09). SB_0 and MSY are not reported for the Short models due to a misspecification scale.

Model	Long Coastwide		Long AAF		Short Coastwide	Short AAF
Regime	**Low**	**High**	**Low**	**High**	**Low**	**Low**
SB_0 (Mlbs)	287-753	407-1,048	368-986	655-1,721		
MSY (Mlbs)	36-84	61-117	36-71	62-124		
RSB_{MSY}	24-26%	23-25%	24-26%	22-25%	24-27%	24-26%
SPR_{MSY}	30-32%	29-32%	31-32%	29-31%	31-33%	30-32%

3.3 MSE OPERATING MODEL

The last twenty years of the estimated reference points from the MSE operating model simulations are shown in Figure 6. This figure does not show the annual change in the reference points for a single trajectory due to changes in the regime and weight-at-age, for example, but the confidence region incorporates the variability within each simulated trajectory as well as across trajectories, which results from parameter uncertainty. Structural uncertainty can be compared between the Long and Short Coastwide models in the left and right panels, respectively. The median and 90% confidence region are stable throughout this time-period because the simulations are far enough in the future that they have come to equilibrium with the consistent application of a management procedure. The high regime results in a higher B0 and MSY and similar RSB_{MSY} and SPR_{MSY} reference points (there is no difference between regimes in the Short model because a regime shift was not specifically modeled). The Short model generally showed higher RSB_{MSY} and SPR_{MSY} reference points compared to the Long model.

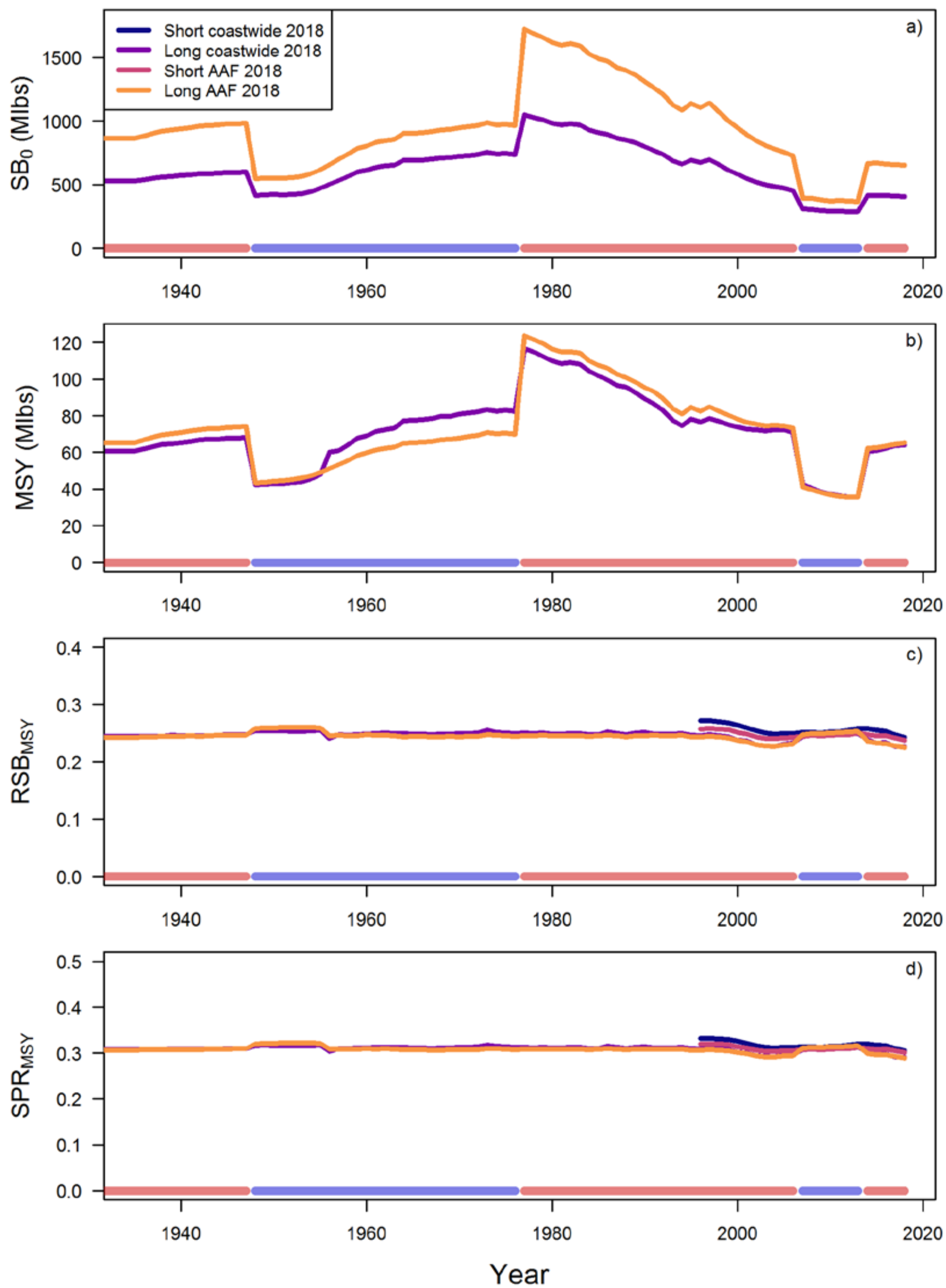

Figure 4. Estimated dynamic equilibrium reference points for B_0 (panel a), MSY (panel b), RSB_{MSY} (panel c), and SPR (panel d) from the four models in the 2018 stock assessment. Estimates of uncertainty were unavailable. SB_0 and MSY for the Short models are not shown due to a misspecification of the scale.

The integrated results overall all sources of uncertainty, including structural uncertainty represented by the two models, are shown in Table 3. The median RSB_{MSY} is 27% with 5th and 95th percentiles at 22% and 32%. The median SPR_{MSY} is slightly higher at 33% with 5th and 95th percentiles at 25% and 41%.

Table 3. MSY reference points integrated over all scenarios and uncertainty using the MSE OM with a random walk for weight-at-age.

Reference Point	5th Percentile	Median	95th Percentile
RSB_{MSY}	22%	27%	32%
SPR_{MSY}	25%	33%	41%

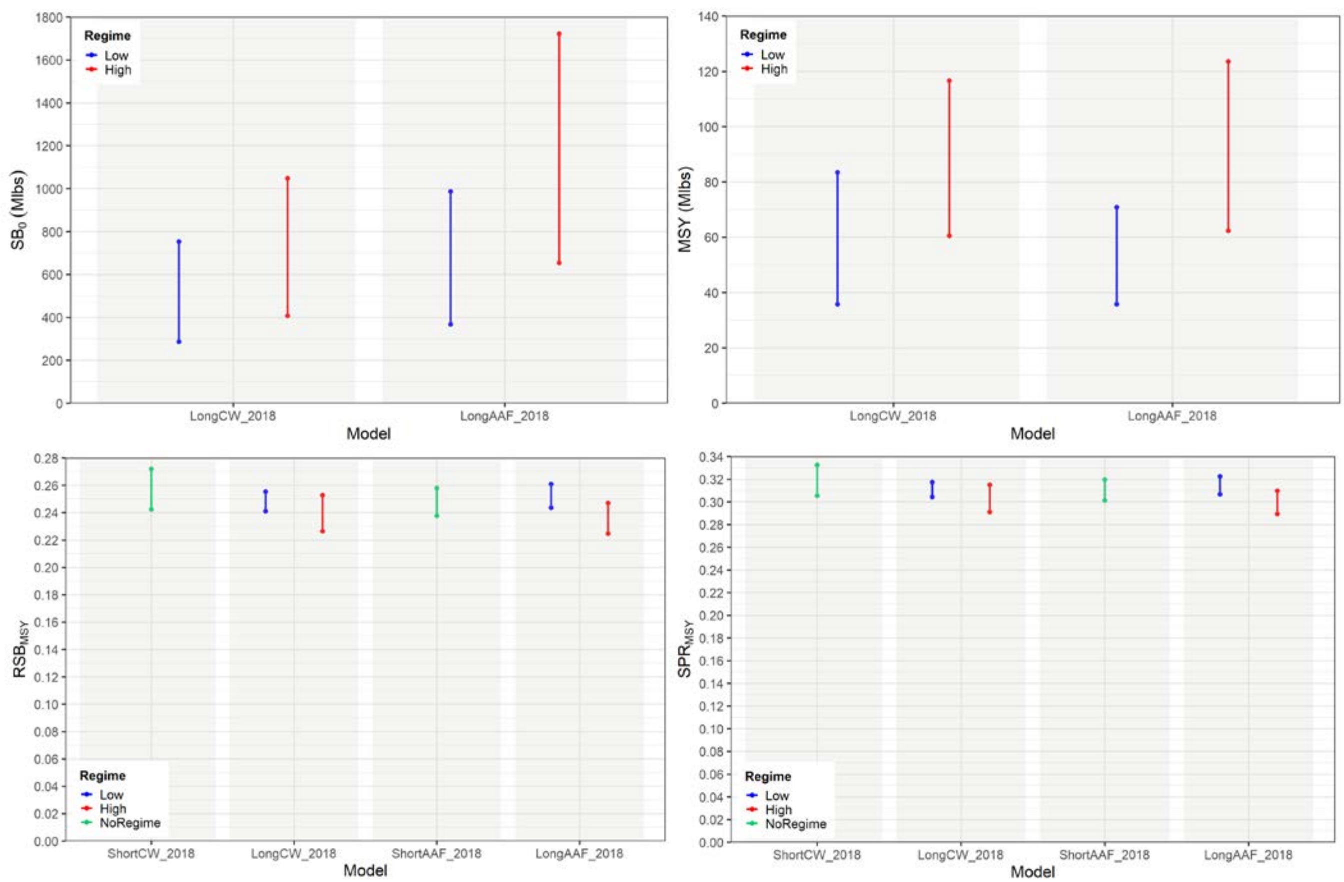

Figure 5. Estimated dynamic equilibrium reference points from the assessment model. Each segment represents the minimum and maximum range of the estimates over the entire time-series of the corresponding model. Two regimes (low in blue and high in red) were modeled in the long time-series models. A single regime (no regime change) was implemented in the short-time-series models (green). SB_0 and MSY for the Short models are not shown due to a misspecification of the scale.

An examination of weight-at-age scenarios showed that changes in B_0 are due to the regime and weight-at-age, and a change in regime is similar to the change from low to medium or low to high weight-at-age (Figure 7). The MSY shows a similar patter of increasing MSY with the higher regime and higher weight-at-age. The relative spawning biomass at MSY (RSB_{MSY}) was lowest with a low regime and low weight-at-age but was very similar across all scenarios at a value slightly below 25% for the Long model and near 28% for the Short model. A similar pattern was seen for SPR_{MSY} with values near 30% and 34% for the Long and Short models, respectively. The Short model did not estimate a regime shift, thus shows similar results regardless of the regime. The results are tabulated in Table 4.

Table 4. MSY reference points (RSB_{MSY} and SPR_{MSY}) for the two models, two recruitment regimes, and three weight-at-age scenarios from the MSE OM analysis.

	Model	**Long Coastwide**							**Short Coastwide**		
	Regime	**Low**			**High**				**No Regime**		
	Weight-at-age	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**		**Low**	**Medium**	**High**
RSB_{MSY}	0.05	19%	19%	20%	20%	19%	20%		22%	23%	23%
	Median	24%	24%	25%	25%	25%	25%		27%	28%	29%
	0.95	28%	28%	29%	29%	29%	29%		32%	33%	33%
SPR_{MSY}	0.05	21%	21%	22%	22%	22%	22%		24%	25%	26%
	Median	29%	30%	30%	30%	30%	30%		33%	34%	34%
	0.95	36%	37%	37%	37%	37%	37%		42%	42%	43%

3.4 SUMMARY AND COMPARISON OF THREE METHODS

The three methods resulted in similar estimates of dynamic equilibrium reference points, with some differences due to the perspective that each method had on uncertainty and variability. The minimum and maximum estimates from the range of scenarios in the equilibrium model and MSE OM model (median estimates), and years in the stock assessment approach show this consistency (Table 5). The equilibrium model produced the widest range of estimates for most reference points because it examined different values of steepness including 0.5 and 0.9. Overall, the estimate of RSB_{MSY} was typically between 20% and 30%, and SPR_{MSY} was between 30% and 35%.

Even though each approach estimated similar reference points, each approach has a unique perspective on the variability and sensitivity. The equilibrium approach took little computer time and allowed for the examination of specific scenarios by altering parameters such as steepness. The assessment approach provided an empirical retrospective look at the dynamic reference points for the Pacific halibut stock. The MSE OM approach was able to integrate over a variety of uncertainties and variability to provide a robust range of likely values for the dynamic reference points.

Table 5. Range (minimum and maximum over weight-at-age and regime scenarios) of estimated dynamic equilibrium reference points (median for the MSE OM) for the three methods.

	Method		
Reference Point	**Equilibrium**	**Assessment**	**MSE**
RSB_{MSY}	15–37%	22–27%	24–29%
SPR_{MSY}	17–52%	29–33%	29–35%

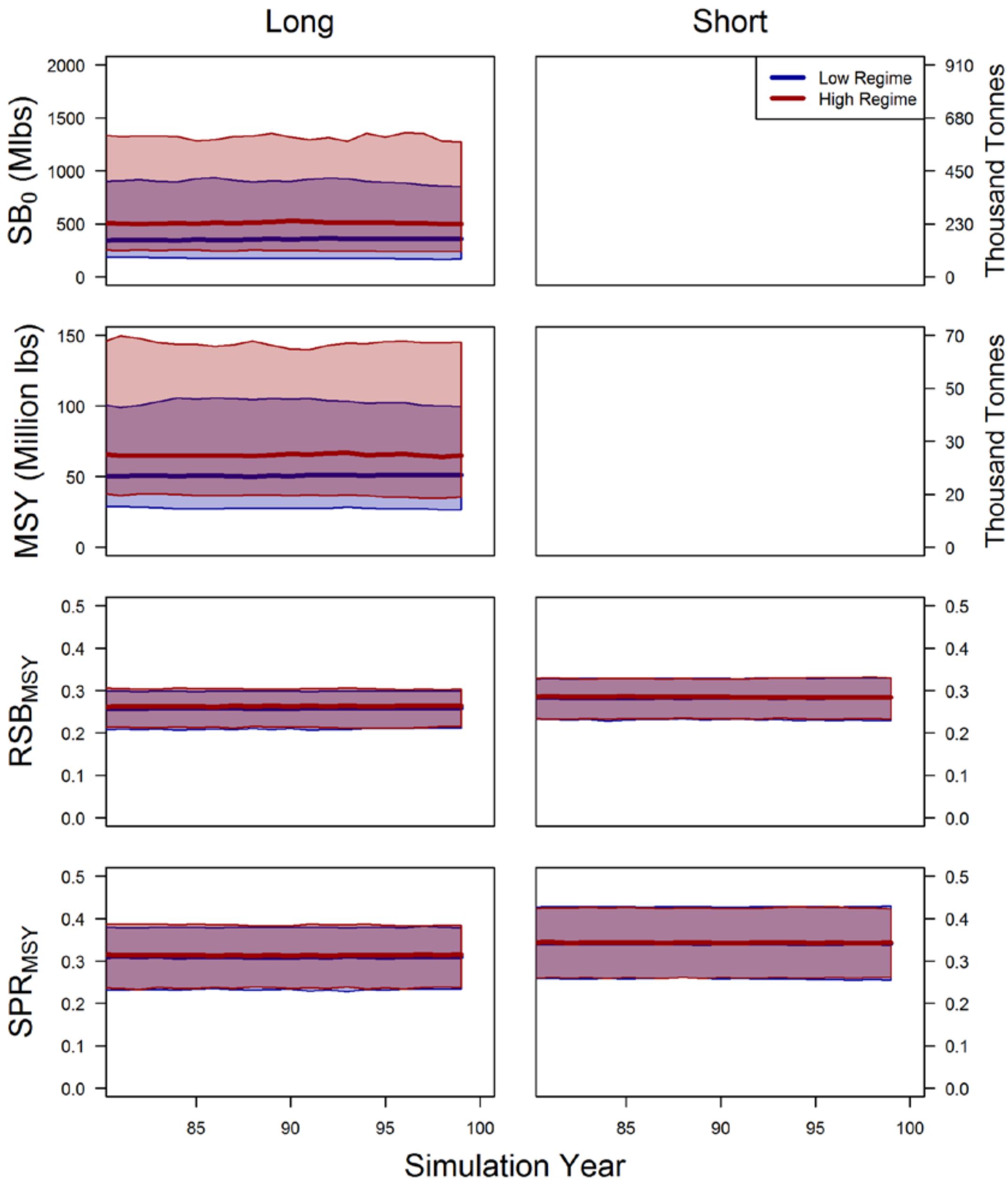

Figure 6. Estimated dynamic equilibrium reference points from the MSE operating model simulated trajectories for low and high environmental regimes (blue and red, respectively), Long and Short Coastwide models (left and right columns, respectively), and with simulated variability in weight-at-age. The median is shown as the thick solid line and the 5th and 95th percentiles are shown as thin lines with the shaded polygon representing a 90% confidence region. Millions of pounds is converted to thousands of tonnes (right axes) for SB_0 and MSY. SB_0 and MSY for the Short models are not shown due to a misspecification of the scale.

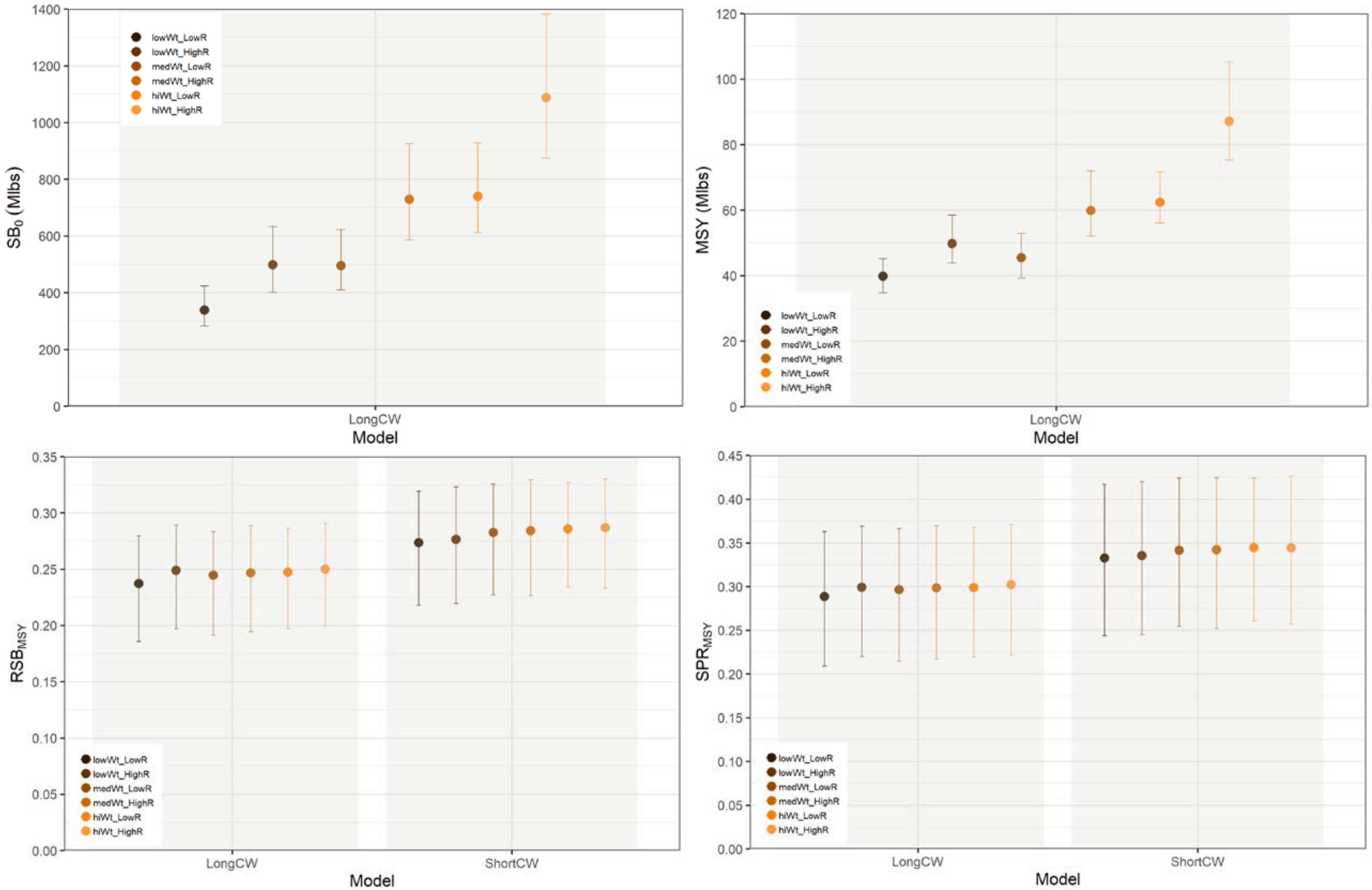

Figure 7. Estimated dynamic equilibrium reference points from the coastwide MSE framework. Vertical bars represent 95% confidence limits. SB_0 and MSY for the Short models are not shown due to a misspecification of the scale.

4 Discussion

The current analysis confirms that depending on the scenario and the level of uncertainty considered, reference points estimates can be quite different, and this is especially true for B_0 and MSY. Despite these differences, the overall level is consistent between models. These results will be useful for determining an appropriate proxy target relative spawning biomass for the IPHC harvest strategy policy and to define an objective for the current MSE analysis. A range of possible values for RSB_{MSY} were determined and many scenarios were examined to provide for an evaluation of the effects of various parameters. Precautionary principles may be invoked based on these scenarios (Gabriel and Mace 1999).

A reasonable RSB_{MSY} proxy, including a precautionary allowance for unexplored sources of uncertainty, would be 30%, and is consistent with reference points estimated for other flatfish species. For example, Punt et al. (2008) reported similar estimates of RSB_{MSY} from simulations based on petrale sole (*Eopsetta jordani*) for steepness values near 0.75. The recent petrale sole stock assessment (Stawitz et al. 2016) estimated RSB_{MSY} near 21% with an estimated steepness of 0.9. An RSB_{MSY} of 30% would put a proxy for SB_{MEY} between 36% and 44% given the recommendations of Rayns (2007) and Pascoe et al. (2014).

Most results for the value of SPR_{MSY} were between 29 and 35%, except where more extreme values of steepness and natural mortality were considered in the equilibrium model. Although it is difficult to estimate steepness in most fisheries data sets, and Pacific halibut are no exception, the 2018 stock assessment and 2019 preliminary assessment show little support for values less than 0.75 (Stewart and Hicks 2019b). Therefore, at present, a working value of SPR_{MSY} = 35% can be seen as precautionary if managing to a target SB_{MSY} was the only management objective.

4.1 Future research

Changes in productivity (average unfished recruitment) and size-at-age affect the stock-recruit relationship when it is assumed to follow a Beverton-Holt formulation.

$$R_y = \frac{(4 * h * R_0 * SB_{y-1})}{(1-h) * SB_0 + (5 * h - 1) * SB_{y-1}} \qquad \text{Eq. 1}$$

where R_y is the recruitment in year *y*, *h* is steepness (the proportion of unfished recruitment realized when the spawning biomas is at 20% of the unfished level), R_0 is equilibrium unfished recruitment, SB_{y-1} is the spawning biomass in the previous year, and SB_0 is the unfished equilibrium spawning biomass. Assuming that steepness remains unchanged over time, R_0 and SB_0 would change with regime shifts and changes in size-at-age, thus changing the shape of the relationship (Figure 8). Changes in R0 change the height of the curve, and for a fixed SB the recruitment would be reduced. In the event of a regime shift that affects only R0, the SB would change very slowly until the first recruits from the regime shift become part of the spawning biomass. Therefore, the dynamics are not suddenly changed by a change in R0, although in equilibrium, the spawning biomass declines with a decrease in R0 (points in the left plot of Figure 8). Similarly, at fixed steepness and fixed R0, changes in weight-at-age result in a change in equilibrium spawning biomass and hence in stock productivity, which changes the shape of the stock-recruit curve (Figure 8 right panel). Because steepness is constant, equilibrium recruitment at 20% of SB0 (and in fact all percentages of SB0) is also constant (triangles in the right panel of Figure 8). This shift in the stock-recruitment curve implies a shift in the egg production (i.e. a lower spawning biomass producing the same number of eggs of a higher spawning biomass, if number of eggs is what determines the number of recruits in the next year).

At constant steepness, the stock-recruit curve is dynamic with changes in the vertical and horizontal directions depending on R0, because R0 affects the height of the curve and the equilibrium spawning biomass. Changes in weight-at-age results in a change to the stock-recruit curve in only the horizontal direction. Since steepness is strictly linked to the demography and the life history parameters of the stock (Mangel et al. 2010), it would be interesting to investigate the effect on reference points of fixing the shape of the stock recruitment curve. However, given the small difference in the curves with different weight at age and steepness of 0.75 (Figure 9), it is expected that the estimated reference points would remain within the same ranges reported here.

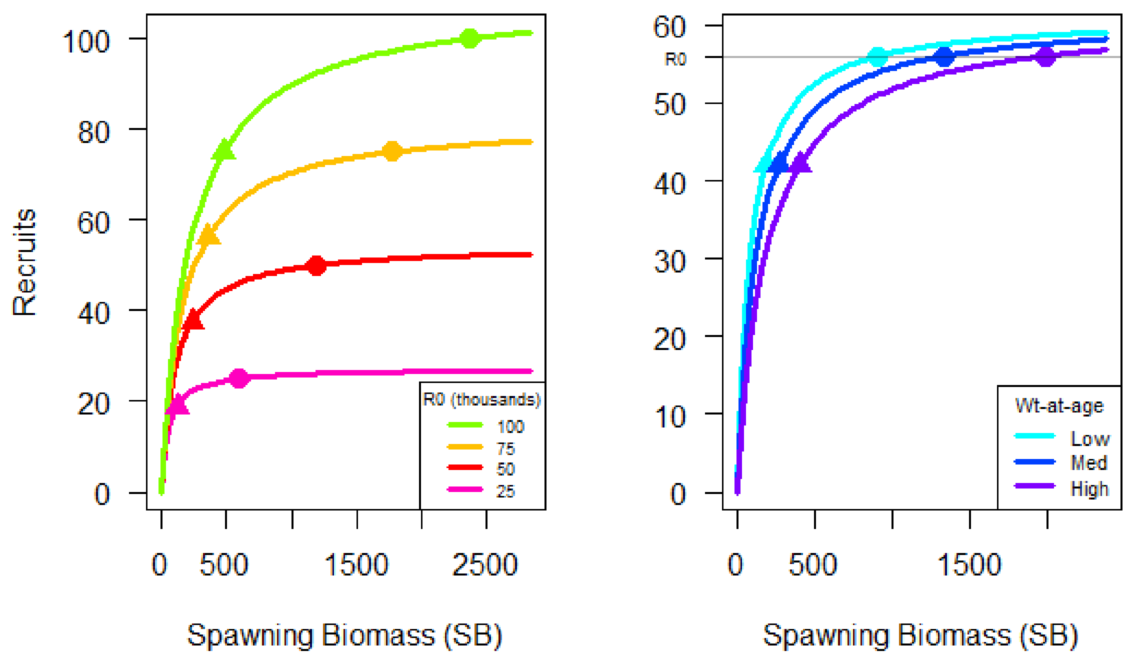

Figure 8: The stock-recruit relationship with a fixed steepness of 0.75 for different levels of R0 (left plot) and different weight-at-age assumptions (right plot). The points in each plot show the equilibrium recruitment at SB0 (circles) and at 20% of SB0 (triangles).

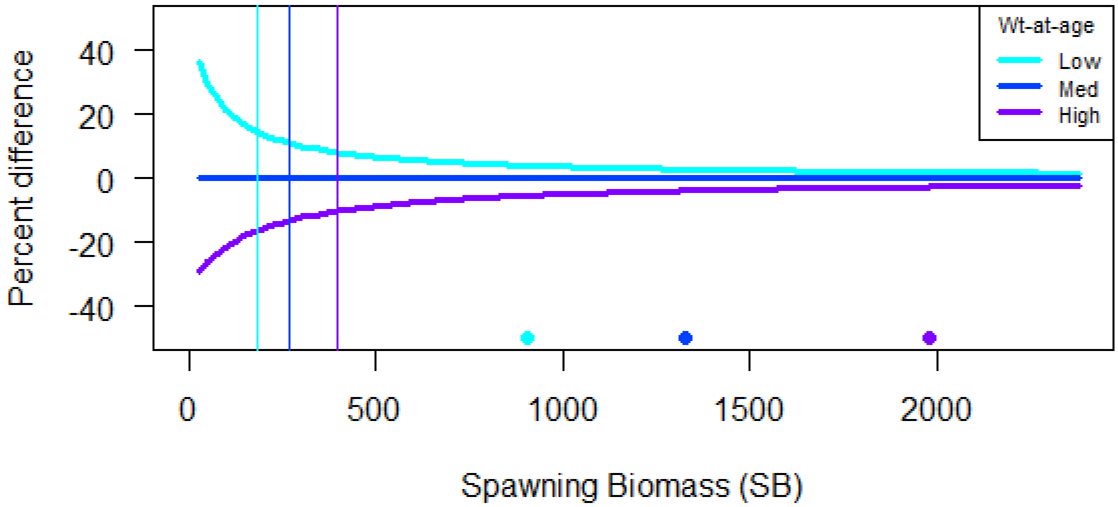

Figure 9: Percent difference of the predicted recruits for low, medium, and high weight-at-age scenarios compared to the medium weight-at-age scenario. Points show SB0 for each scenario and the vertical lines show 30% of SB0 for each weight-at-age scenario.

This analysis of dynamic equilibrium reference points for Pacific halibut used the best available information at this time. Research continues for Pacific halibut and the stock assessment is being updated in 2019, and this analysis may be improved by incorporating results from future research and stock assessments. Additionally, the Short Coastwide model did not include a link between the environmental regime and R_0, but it might be useful to investigate the effect when using the environmental link estimated from the Long Coastwide model.

Additional analyses of the results produced here may be useful for purposes other than determining appropriate reference points and targets. For example, examining specific trajectories to determine the range of the annual relative spawning biomass given various sources of variability and how much those deviate from the target reference point would provide insight into what a target means in the context of Pacific halibut management. The equilibrium model and MSE OM model would both be able to produce these results.

5 RECOMMENDATIONS

That the SRB:

1. **NOTE** paper IPHC-2019-SRB015-11 Rev_1 which presents dynamic equilibrium reference points for Pacific halibut estimated using three different methodologies.
2. **NOTE** the estimate of dynamic equilibrium RSB_{MSY} for Pacific halibut was likely in the range of 20% to 30% and SPR_{MSY} was likely between 30% and 35%.
3. **RECOMMEND** improvements and modifications to paper IPHC-2019-SRB015-11 Rev_1 for presentation at MSAB014 to facilitate the discussion of an objective related to a biomass target.

6 REFERENCES

Berger, A. M. 2019. Character of temporal variability in stock productivity influences the utility of dynamic reference points. Fisheries Research 217: 185-197.

Clark, W. G. and Hare, S. R. 2002. Effects of climate and stock size on recruitment and growth of Pacific halibut. North American Journal of Fisheries Management 22: 852-862.

Clark, W. G. and Hare, S. R. 2006. Assessment and management of Pacific halibut: data, methods, and policy. International Pacific Halibut Commission Scientific Report No. 83. 104 p.

Gabriel, W. L. and Mace, P. M. 1999. A review of biological reference points in the context of the precautionary approach. Proceedings, 5th NMFS NSAW. NOAA Tech. Memo. NMFS-F/SPO-40: 34-45.

Harley, S., Davies, N., Hampton, J. and McKechnie, S. 2014. Stock assessment of bigeye tuna in the western and central Pacific ocean. Ocean Fisheries Programme. Secretariat of the Pacific Community, Noumea, New Caledonia. WCPFC-SC10-2014/SA-WP-01 Rev1 25 July. 115 p.

Hicks, A. C. and Stewart, I. J. 2018. IPHC Management Strategy Evaluation to investigate fishing intensity. International Pacific Halibut Commission. IPHC-2018-MSAB012-07 Rev_1.

Larkin, P. A. 1977. An epitaph for the concept of maximum sustained yield. Transactions of the American Fisheries Society 106(1): 1-11.

Mangel, M., Brodziak, J. and DiNardo, G. 2010. Reproductive ecology and scientific inference of steepness: a fundamental metric of population dynamics and strategic fisheries management. Fish and Fisheries 11(1): 89-104.

Mangel, M., MacCall, A. D., Brodziak, J., Dick, E. J., Forrest, R. E., Pourzand, R., Ralston, S. and Rose, K. 2013. A perspective on steepness, reference points, and stock assessment. Canadian Journal of Fisheries and Aquatic Sciences 70(6): 930-940.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. and Francis, R. C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78(6): 1069-1079.

Methot, R. D. and Wetzel, C. R. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research 142: 86-99.

NPFMC. 2018. Fishery management plan for groundfish of the Bering Sea and Aleutian Islands management area. North Pacific Fishery Management Council, 605 W. 4th Ave, Suite 306, Anchorage, AK 99501. 174 p.

Pascoe, S., Thebaud, O. and Vieira, S. 2014. Estimating proxy economiuc target reference points in data-poor single-species fisheries. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 6(1): 247-259.

PFMC. 2016. Pacific Coast groundfish fishery management plan for the California, Oregon, and Washington groundfish fishery. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, OR 97220. 160 p.

Punt, A. E., Dorn, M. W. and Haltuch, M. A. 2008. Evaluation of threshold management strategies for groundfish off the U.S. West Coast. Fisheries Research 94(3): 251-266.

Rayns, N. 2007. The Australian government's harvest strategy policy. ICES Journal of Marine Science 64: 596-598.

Schaefer, M. B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bulletin of the Inter-American Tropical Tuna Commission 1(2): 27-56.

Stawitz, C. C., Hurtado-Ferro, F., Kuriyama, P., Trochta, J. T., Johnson, K. F., Haltuch, M. and Hamel, O. S. 2016. Stock assessment update: status of the U.S. petrale sole resource in 2014. Pacific Fishery Management Council, Portland, OR. .

Stewart, I. J. 2017. Overview of data sources for the Pacific halibut stock assessment adn related analyses. International Pacific Halibut Commission Report of Assessment and Research Activities 2016. 279-364.

Stewart, I. J. and Martell, S. J. D. 2016. Appendix: Development of the 2015 stock assessment. International Pacific Halibut Commission Report of Assessment and Research Activities 2015. A1-A146.

Stewart, I. J. and Hicks, A. C. 2019a. Assessment of the Pacific halibut (*Hippoglossus stenolepis*) stock at the end of 2018. International Pacific Halibut Commission. IPHC-2019-AM095-09 26 p.

Stewart, I. J. and Hicks, A. C. 2019b. Updates on the development of the 2019 stock assessment. International Pacific Halibut Commission. IPHC-2019-SRB015-07. 10 p.

7 APPENDICES

I. Calculating dynamic equilibrium reference points from the equilibrium model

II. Calculating dynamic equilibrium reference points from the stock assessment

III. Calculating dynamic equilibrium reference points from the MSE operating model

APPENDIX I: CALCULATING DYNAMIC EQUILIBRIUM REFERENCE POINTS FROM THE EQUILIBRIUM MODEL

The equilibrium model that was built to carry out the deterministic projections uses simple population dynamics equations to project the population 200 years in the future to ensure it reaches equilibrium conditions. The model first retrieves biological and fishery information by sex on the halibut stock from the stock synthesis Long-Coastwide assessment model (i.e. weight at age, natural mortality, maturity at age, selectivity at age by fleet). For the purpose of this work, the fishery dynamics have been simplified to 2 fleets only: a commercial and a non-directed discard mortality (bycatch) fleet.

The simulation loops through exploitation rates values from 0 to 1 by 0.001 steps. At each loop, it initiates the population using assumptions on R_0 (high or low regime), natural mortality values and the exploitation rate being tested. The fleet-specific exploitation rates (U_f) were a defined proportion of the total exploitation rate (U) being tested:

$$U_f = U \times p_f$$

Where p_f is 0.80 for the commercial fleet and 0.20 for the non-directed discard mortality fleet. Exploitation rate by age and sex is found using the selectivity (S) at age and sex for each fleet.

$$U_{a,s,f} = U_f * S_{a,s,f}$$

The population was initialized at levels near equilibrium and then simulated forward in time as follows:

$$N_{y,a,s} = N_{y-1,a-1,s} * e^{-M_{a-1,s}} * (1 - U_{a-1,s})$$

Where $U_{a,s}$ is the sum of the exploitation rate by age and sex of all fleets.

For each year of the projection the spawning stock biomass (SB) is calculated,

$$SB = N_{y,a,s} * W_{y,a,s} * mat_{a,s}$$

and a Beverton-Holt spawner recruitment function is used to calculate each subsequent recruitment:

$$R_y = \frac{(4 * h * R_0 * SB_{y-1})}{(1-h) * B_0 + (5 * h - 1) * SB_{y-1}}$$

Steepness (h) values of 0.5, 0.75 and 0.9 where tested.

Catch (in weight) by sex and by fleet are obtained for each year multiplying the numbers at age by the exploitation rate and weight-at-age:

$$C_{y,a,s,f} = N_{y,a,s} * U_{y,a,s,f} * W_{a,s,f}$$

Total catch for each year is simply the sum of $C_{y,a,s,f}$ over ages, sexes, and fleets.

The exploitation rate that produced the maximum yield is determined from the last year of the two-hundred-year projection. This is U_{MSY} and the maximum yield is MSY. RSB_{MSY} and SPR_{MSY} are then calculated using the corresponding equilibrium (i.e., last year of the projection) recruitment and spawning biomass at MSY.

$$RSB_{MSY} = \frac{SB_{MSY}}{SB_0}$$

$$SPR_{MSY} = \frac{SB_{MSY}/R_{MSY}}{SB_0/R_0}$$

APPENDIX II: CALCULATING DYNAMIC EQUILIBRIUM REFERENCE POINTS FROM THE STOCK ASSESSMENT

The 2018 stock assessment (IPHC-2019-AM095-09) was used to retrospectively calculate dynamic equilibrium reference points. The stock assessment consists of four models, each using the Stock Synthesis platform (SS version 3.24;(Methot and Wetzel 2013)). Stock Synthesis does not automatically calculate these dynamic equilibrium reference points for each year, but it does calculate static equilibrium reference points given specifications of parameters such as selectivity, weight-at-age, and R_0 without any environmental adjustments. Therefore, the stock synthesis platform was used to calculate annual dynamic equilibrium reference points by specifying the selectivity, weight-at-age, and R_0 in the static equilibrium reference point determination. Staring from the final year (2018) and working backwards through each year, the algorithm was as follows.

1. Set the forecast.ss file to use most recent year for benchmarks in the equilibrium calculations. Set the starter.ss file to read from the ss3.par file and to not estimate parameters (i.e., last phase = 0).
2. **Long models only**. Determine R_0 for the two environmental regimes. Environmental regime 0 is simply R_0. Environmental regime 1 is R_0*e^(δ), where δ is the estimated environmental link parameter to adjust R_0. Only the long models have an environmental link estimated.
3. **Long models only**. Determine the current (2018) environmental regime and modify R_0 in the ss3.par file using the appropriate value from step 2.
4. Modify the weight-at-age file (wtatage.ss) to use 2018 weight-at-age.
    4.1. Copy the year of interest (2018), delete all lines of weight-at-age, then paste in the year of interest weight-at-age with a negative start year to use that weight-at-age only for all years. The model trajectory won't be right, but the calculated reference points will reflect that weight-at-age.
5. Run SS to calculate reference points without changing anything else from the final assessment (no estimation). The MSY reference points for the final year (2018) are found in the Report.sso file under derived quantities.
6. Loop backwards from (final year -1) to start year.
    6.1. **Long models only**. Determine the environmental regime for the year of interest and modify R_0 in the ss3.par file using the appropriate value from step 2 above.
    6.2. Modify the wtatage.ss file to use year of interest of weight-at-age as in step 4.1.

6.3. Modify the last selectivity parameter deviations to be the deviations for the year of interest.

6.4. Run SS without estimation to calculate the reference points for year of interest.

6.5. Repeat these steps under #6.

APPENDIX III: CALCULATING DYNAMIC EQUILIBRIUM REFERENCE POINTS FROM THE MSE OPERATING MODEL

The MSE operating model was used in the recent coastwide MSE to simulate the population forward for 100 years using various management procedures (IPHC-2018-MSAB012-07). Any of these simulations may be used to calculate dynamic equilibrium reference points because there is no density-dependence on weight-at-age or selectivity. Therefore, the procedure that was used for the stock assessment evaluations (Appendix II) was also used for the MSE OM evaluations, except that the final year was the last year in the 100-year projection, and the algorithm worked backwards for 50 years. This was done for 500 different simulated trajectories under low and high recruitment regimes for the Long Coastwide model, and 1000 simulated trajectories for the Short Coastwide model. The simulated trajectories were first created for the specific regime with fishing occurring at an $F_{SPR=46\%}$, although it does not matter what level of fishing occurred. The algorithm in Appendix II was then used to calculate dynamic equilibrium reference points.