Defining the Simulations to Evaluate Fishing Intensity

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PURPOSE

To inform the Scientific Review Board (SRB) about and solicit feedback for the framework and inputs to the closed-loop simulations used to investigate measures of and specific values for fishing intensity (e.g., F_{SPR}). Fishing intensity defines the scale of fishing in the IPHC harvest policy, and these simulations will help to determine a specific fishing intensity that will best meet the goals and objectives defined by the MSAB. The expected outcome of this discussion will be a review of the decisions made at MSAB09 and by IPHC staff to define the necessary components of the closed-loop simulations as well as improvements to the harvest policy so that work can continue and results can be presented at the October MSAB meeting (MSAB10).

INTRODUCTION

A 2-year work plan was developed outlining a schedule for implementing a Management Strategy Evaluation (MSE) to investigate management procedures for the Pacific halibut fishery (IPHC-2016-MSAB08-11). The draft workplan was provided to the MSAB07 in May 2016 and was revised by the MSAB08 in October 2016. As tasked by the Commission, and described in the workplan, an evaluation of the current harvest policy was undertaken and presented at MSAB08.

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

The stock assessment predicted a 68% chance that the spawning biomass will decline in 2017 and a 6% chance that it will decline more than 5% with the status quo SPR fishing intensity (Table 4 in Stewart and Hicks (2017)). The greater than 50% chance of decline, although a slight decline, indicates that the status quo SPR may not determine a fishing intensity that will meet the long-term goals and objectives defined by the MSAB. Therefore, an evaluation of fishing intensities, through simulation, should be done to determine a fishing intensity that meets those long-term goals and objectives. The framework and components of these simulations are described below, and the SRB is asked to comment on both, as well as to determine the appropriate inputs.

FRAMEWORK

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

1. The **Operating Model (OM)** is a representation of the population and the fishery. It produces the numbers-at-age, accounting for mortality and any other important processes, and also incorporates uncertainty in the processes.
2. **Monitoring (data generation)** is the code that simulates the data from the operating model that is used by the estimation model. It can introduce variability, bias, and any other properties that are desired.

3. The **Estimation Model (EM)** is analogous to the stock assessment. Using the data generated, it produces an annual estimate of stock size and status and provides the advice for setting the catch levels for the next time step.
4. **Harvest Strategy** is the application of the estimation model output along with the scale and distribution management procedures (Figure 1) to produce the catch limit for that year.

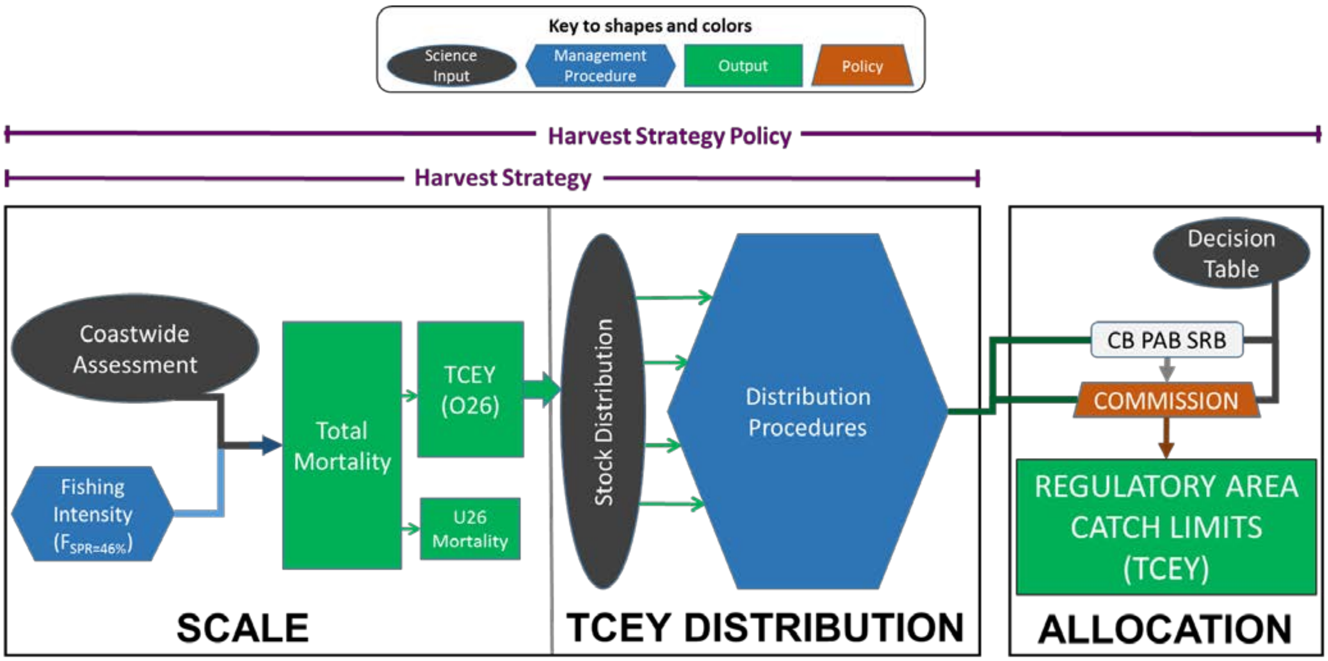

Figure 1: A revised harvest policy showing the separation of scale and distribution of fishing mortality. Allocation is when policy (not a procedure) influences the final decision.

OPERATING MODEL

The operating model represents an uncertain reality, or the states of nature. In other words, it is a computer program that simulates a population that one would normally not observe in its entirety. For example, this could be a model for the coastwide halibut population.

An operating model may be simple or complex, depending on the outcomes desired, and is designed to simulate a population given a set of pre-defined parameters. The scope of the parameter set depends on the defined complexity. These parameters may define natural mortality, recruitment, selectivity, or migration, or be related to any number of processes.

Uncertainty in the simulated population is introduced in two different ways: parameter uncertainty and model uncertainty. Parameter uncertainty involves changing the parameters to reflect the range of possible values for those parameters. The most straightforward way to introduce parameter uncertainty is to simply change the parameter from one value to another (e.g., change natural mortality from 0.15 to 0.2). This is more like a sensitivity analysis and does not best represent the range of estimated values for that parameter, although it could indicate the extremes or specific quantiles or the results could integrate over the two values similar to how an ensemble of models works. A more complete and integrated approach is to sample parameter values from a joint probability distribution to apply to the operating model. This joint distribution may be determined from data.

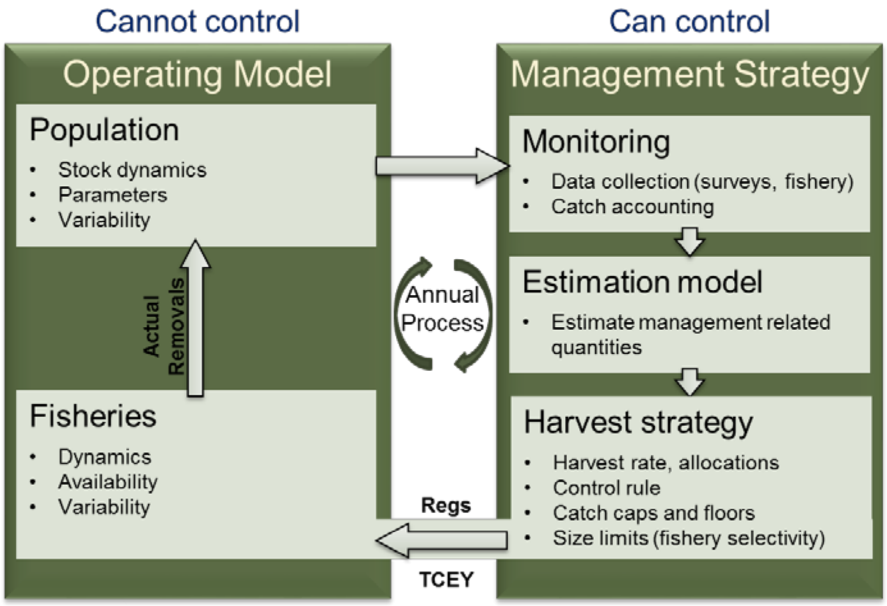

Figure 2: Diagram of the relationship between the four modules in the framework. The simulations run each module on an annual time-step, producing output that is used in the next time-step. The operating model contains elements that we cannot control, and the management strategy contains elements that we can control.

Model uncertainty involves a change to the model structure or specification. For example, it may be adding a specific migration assumption, introducing density-dependence on recruitment or growth, or even changing the way that a fishery (e.g., bycatch) interacts with the population.

Ideally, the simulations would integrate over a range of scenarios (potential states of nature) by drawing parameters from a joint probability distribution and integrating over multiple model structures. This is similar to the ensemble modeling approach used for the Pacific halibut stock assessment, except that the scenarios could be more theoretical rather than practical. For the current stock assessment, it is not practical to fit a migration model to data and provide reasonable management advice until there is a better understanding of Pacific halibut migration. However, for the MSE simulations, supplying hypothetical, yet reasonable, migration models as scenarios will be useful to evaluate the potential effects of migration on the outcomes. In other words, it is an additional source of uncertainty in the state of nature. Potential scenarios are described in a separate section below.

Simulating processes like size at age, recruitment, recruitment regime, and others requires some assumptions about the temporal trends or changes in those processes. These processes cannot specifically be controlled by a management procedure, thus are used as scenarios in the operating model. These processes and other scenarios are discussed further in the Scenarios section below.

The operating models can be a mix of programs and code, as long as they all have the outputs needed for the other modules. For the simulations to investigate a coastwide fishing intensity, I propose to use the Stock Synthesis (Methot and Wetzel 2013) assessment program that is currently used for the stock assessment, and due to time available, some or all of the assessment models currently used in the ensemble. For future MSE evaluations (in particular, investigating the Distribution component of the harvest policy) a more complex operating model will need to be developed that can provide outputs by defined areas or regions and can account for migration between these areas. This model has been referred to as a multi-area model.

The current ensemble composed of four different assessment models includes a cross between coastwide or fleets-as-areas, and the length of the time series. Using a fleets-as-areas model would require generating data and distributing catch to four areas of the coast, which would involve many assumptions. In addition, without a multi-area model, there would not be the feedback from migration and productivity of harvesting in different areas. Therefore, I propose to use the two coastwide models, with additional variability. These models use five fisheries: commercial, wastage, bycatch, sport, and personal use, and the TCEY will have to be distributed to each fleet (see Scenarios). The survey is also included as a fleet without catch.

MONITORING (DATA GENERATION)

The operating model represents the population and the data generation model simulates the process of collecting data from that population. There are many data collection programs in fisheries, but we will focus on the data needed in the estimation model (i.e., coastwide stock assessment model) and the harvest strategy (i.e., distribution). In the sequence of the simulation, data generation occurs between the operating model and estimation model. The data types to be generated are listed in Table 1.

Table 1: Data to generate and information about each.

Data	Type	Area	Frequency	Sexes	Probability Distribution	Bias[1]	Uncertainty
Survey total NPUE	Fishery-independent	Coastwide	Annual	Combined	Lognormal	No	From Assessment
Age composition for survey total numbers	Fishery-independent	Coastwide	Annual	Two sexes	Dirichlet	Possibly selectivity	From Assessment
WPUE for the directed commercial fishery	Fishery-dependent	Coastwide	Annual	Combined	Lognormal	Assumptions about catchability	From Assessment
Age composition from the directed commercial fishery	Fishery-dependent	Coastwide	Annual	Combined	Dirichlet	Possibly selectivity	From Assessment
U26 age composition from the survey (proxy for wastage)	Fishery-independent	Coastwide	Annual	Two sexes	Dirichlet	Possibly selectivity	From Assessment
Age composition for the bycatch fisheries.	Fishery-dependent	Coastwide	Annual	Combined	Dirichlet	Possibly selectivity	From Assessment
Age composition for the sport fishery.	Fishery-dependent	Coastwide	Annual	Combined	Dirichlet	Possibly selectivity	From Assessment

[1]Bias is whether there is a difference between the generated data and the EM assumptions.

Estimation Model

The estimation model in MSE simulations mimics the stock assessment, or the model and process used to estimate quantities needed for the harvest strategy from which to provide catch advice. At IPHC, the stock assessment is based on four models using the Stock Synthesis framework. The results from the four models are combined to produce uncertainty related to observation error and structural error, which is then translated into the decision table presented to Commission. One line in that decision table contains estimated catch levels consistent with the current harvest policy.

To capture the uncertainty of the stock assessment in the MSE simulations, the estimation quantities needed for catch advice are simulated with the estimation model. Simulating an annual stock assessment can be time-consuming, but is important to capture that source of variability. The following set of methods for simulating the stock assessment are proposed to choose from.

- **Perfect Information**: This assumes that the quantities necessary for applying the harvest strategy and determining catch levels for the next year are known exactly and without estimation error. In other words, the Commissioners would have perfect information to guide them on their decision. It is not quite an omniscient Commission because they would only know the information for the current year and not all of the necessary information to maximize objectives in the future.
- **Simulate Error**: The method would simply take the simulated abundance/biomass from the operating model and apply variability to it. It is likely that this variability would be lognormal, which introduces a long tail for uncertain higher values, and forces the randomly generated value to be greater than zero. This is an approximation to the stock assessment with simplistic assumptions of constant error across all levels of abundance/biomass and no bias, but could be expanded to model variability as a function abundance/biomass and even introduce bias in some way. However, it will always be an approximation that does not take into account the types of data collected, the frequency of data collected, and the correlation of error given historic (unchanging) data.
- **Single Stock Assessment**: An actual stock assessment model can be run using the data generated during the Data Generation step. For example, one of the models used in the ensemble could be run to estimate the necessary inputs to the harvest strategy (i.e., catch at F_{SPR} and stock status). Running an age-structured stock assessment model like Stock Synthesis can be time-consuming, and doing that annually in the simulations can significantly increase the time for a run to complete. However, using the actual stock assessment model in the simulations captures the nuances of the combinations of data and will produce results that are more similar to what may be expected in practice.
- **Ensemble of Models**: An ensemble of four stock assessment models is currently used for short-term catch advice at IPHC. This process would be similar to running the single stock assessment model, except that it would run four models and then combine the results. Using parallel processing in modern day computers may not significantly increase the run time, except that the ensemble would be as slow as the slowest model. In addition, there are increased chances for a model not converging and causing further delays in the simulations.

Of the four options above, the Perfect Information option will likely be used as a reference to the performance without the uncertainty in an estimation model. It is unlikely that a full Ensemble of Models will be used due to the increased difficulty in running and monitoring four models. A potentially useful plan would be to blend the Simulate Error and Single Stock Assessment options by using a single stock assessment, and adding additional error to that to mimic results from an ensemble. If time allows, the possibility of using the two or more models from the ensemble of four may be explored.

HARVEST STRATEGY

The harvest strategy to evaluate is shown in Figure 1, but the focus will be on the Scale portion to produce results for the MSAB to evaluate before AM094. In addition to fishing intensity, a control rule is sued to adjust the fishing intensity at low stock status. This is discussed below in the Management Procedures section. For these simulations, I propose to use the two coastwide models, thus do not need to distribute the catch or survey observations to areas.

SUMMARY OF THE FRAMEWORK

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

1) Operating Model
    a) Stock synthesis, based on coastwide assessment models (short and long models).
    b) Five fleets, as in the assessment models (commercial, wastage, bycatch, sport, personal use).
    c) Uncertainty incorporated through parameter uncertainty and model uncertainty. See Scenarios.
2) Estimation Models
    a) Perfect Information (as a reference for how good can we do).
    b) Ensemble of two coastwide models (if not too time consuming).
3) Harvest Strategy
    a) A coastwide fishing intensity
    b) A control rule
    c) Catch assigned to sectors based on historical information (with variability, see Scenarios)
4) Data Generation
    a) Generate survey NPUE and age compositions
    b) Generate commercial WPUE and age comps, bycatch age comps, and sport age comps.
    c) Base error on assessment results.
    d) Introduce bias via selectivity and assumptions about catchability.

SCENARIOS

Scenarios are alternative states of nature in the operating model, which are represented by parameter and model uncertainty, as described above. These alternative states of nature integrate over the uncertainty in the system that we cannot, or choose not to, control. The scenarios for the MSE simulations may include uncertainty in the operating model processes as described in Table 2 and in the monitoring and estimation model components as described in Table 3.

Table 2: Processes and associated uncertainty in the operating model (OM) to potentially include as scenarios in the simulations. TM refers to total mortality.

Process	Uncertainty
Natural Mortality (M)	Attempt to estimate when conditioning OM
Recruitment	Random, lognormal deviations, variability 0.65
Size-at-age	Trend in size-at-age (random walk).
Maturity-at-age	Variable a50; possibly a function of size-at-age
Steepness	Attempt to estimate when conditioning OM
Regime Shifts	Autocorrelated index as indicator (PDO) for regime shift
TM to sectors	See section on allocating TCEY to sectors
Proportion of TCEY	Sector specific. Sum of proportion of TCEY across sectors may not be 100%

Table 3: Processes and associated uncertainty related to the monitoring (DG) and estimation model (EM) components to potentially include as scenarios in the simulations. TM refers to total mortality.

Process	**Uncertainty**
Natural Mortality (*M*)	As in assessment models
Recruitment	As in assessment models
Size-at-age	Fixed from data, as in assessment models
Maturity-at-age	Fixed, from assessment models
Steepness	Fixed, from assessment models
Regime Shifts	Autocorrelated index as indicator (PDO) for regime shift
Fishery Selectivity	Time-varying, possibly different for DG and EM
Survey Selectivity	Time-varying, possibly different for DG and EM
WPUE catchability	Random walk as in assessment, possibly different for DG and EM
Survey catchability	Constant
TM by sector	Small error in EM for wastage, bycatch, sport, and personal use.

ALLOCATING SIMULATED TOTAL MORTALITY TO SECTORS

The simulated management strategy will return a coastwide recommended TCEY, which will have to be allocated to each of the five sectors, with variability. There is a slight difference between the Total Mortality (TM) and the TCEY because of underages and overages, but those should be dealt with on a sector basis. The MSAB09 meeting in May 2017 noted that catch history, in conjunction with uncertainties and sensitivities, can be used to attribute TM to each sector. Recent proportions of TM for each sector will be used to guide the allocation, and relationships of proportions to the TM will be used, such as at low TM the bycatch is likely a larger proportion. Figure 3 shows the percentage of TM attributed for each sector for the past 40 years.

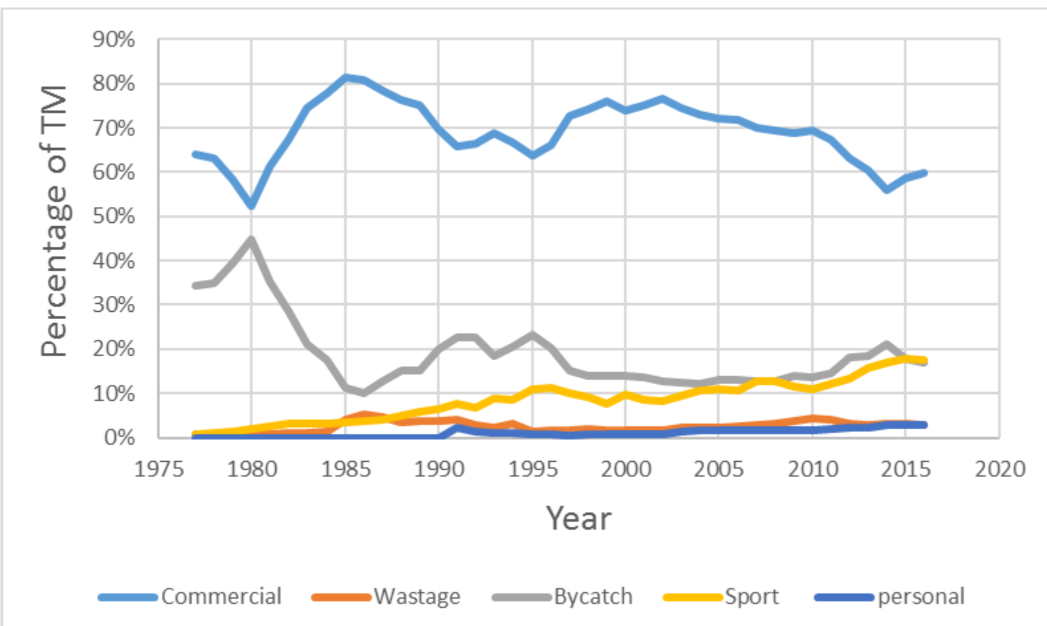

Figure 3: Percentage of Total Mortality (TM) for each sector used in the assessment model from 1976 to 2016.

The TM for the personal use sector has been between 1.1 Mlbs and 1.5 Mlbs for the last ten years, and a consistent 1.20 Mlbs for the last three years (Table 4). Therefore, simply randomly drawing a TM for the personal use sector from a log-normal distribution with a median of 1.2 Mlbs and a CV of 15% would provide 5th and 95th percent quantiles of approximately 0.9 and 1.5 Mlbs. This randomly generated poundage would be the TM for the personal use sector.

Bycatch is a non-directed fishery component of the TM, and is subtracted from the TCEY leaving the remaining amount as the FCEY. It is often managed as a static amount (e.g., fixed PSC limits), but the TM has typically been less than the caps. This has resulted in bycatch being a larger proportion of the TM when the TM is low (Figure 4). Because bycatch will not necessarily go to zero as the directed fishery catch goes to zero, the relationship of bycatch mortality is likely curvilinear. Fitting a loglinear function to the observations of TM and percentage of bycatch results in

$$Bycatch_{proportion} = 0.4346 - 0.067\ln(TM) \qquad (1)$$

The percentage of bycatch would be 13% at a TM of 90 Mlbs and 19% at a TM of 40 Mlbs. At 10 Mlbs, the percentage of bycatch would be 28%, but different assumptions may need to be made when simulated Total mortality is low, such as a constant underlying level of bycatch, with variability. Using the equation above, and assuming an minimum of 7 Mlbs of bycatch, Equation (1) would only predict the percentage to about 36 Mlbs (that results in a bycatch near 7 Mlbs) and then bycatch would be constant below that TM.

A similar investigation occurred for sport fishery mortality, but it appears that the percentage of sport mortality was consistently around 12% during the early 2000’s when the TM was above 50 Mlbs (Figure 4). However, since 2013, and when the TM has been less than 50 Mlbs, the percentage of sport mortality has been larger than 15%. There were significant changes to the catch sharing plans in the last few years, which could help explain this increase in the percentage of sport mortality. Therefore, the MSAB suggested (at MSAB09) to look at more recent years to determine how to simulate sport mortality.

Once personal use, bycatch, and sport mortalities are determined, the commercial plus wastage mortality would be the remaining amount. The wastage component of the commercial+wastage mortality would be calculated using an age proxy for the quantity of O32 in the population.

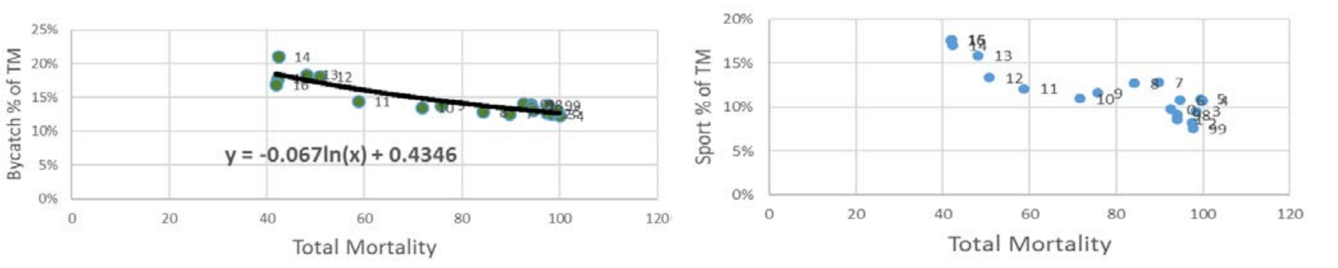

Figure 4: Percentage of bycatch (left) and sport (right) Total Mortality (TM) plotted against TM for the years 1998-2016. Two-digit numbers indicate the year of that observation.

Table 4: Total mortality (Mlbs) for the five sectors used in the assessment model. Numbers are from Stewart (2017), and verified with the assessment mode files for correctness.

Year	Commercial	Wastage	Bycatch	Sport	Personal	Total
1993	59.27	2.05	15.96	7.73	0.93	69.98
1994	54.73	2.51	16.95	7.07	0.93	65.24
1995	43.88	0.93	15.93	7.46	0.54	52.81
1996	47.34	1.15	14.46	8.08	0.54	57.11
1997	65.20	1.45	13.51	9.03	0.54	76.22
1998	69.76	1.72	13.16	8.59	0.74	80.81
1999	74.31	1.65	13.54	7.38	0.75	84.09
2000	68.29	1.45	13.02	9.01	0.76	79.51
2001	70.70	1.69	12.88	8.10	0.77	81.26
2002	74.66	1.72	12.33	8.01	0.77	85.16
2003	73.14	2.08	12.31	9.35	1.38	85.95
2004	73.11	2.3	12.29	10.71	1.55	87.67
2005	71.82	2.22	12.97	10.86	1.54	86.44
2006	67.98	2.46	12.49	10.2	1.48	82.12
2007	62.87	2.59	11.31	11.47	1.49	78.42
2008	58.57	2.76	10.86	10.68	1.34	73.35
2009	52.05	2.94	10.54	8.79	1.31	65.09
2010	49.72	3.21	9.70	7.85	1.24	62.02
2011	39.51	2.46	8.47	7.10	1.14	50.21
2012	31.99	1.67	9.20	6.78	1.15	41.59
2013	29.04	1.43	8.83	7.63	1.13	39.23
2014	23.70	1.30	8.92	7.19	1.20	33.39
2015	24.67	1.28	7.49	7.46	1.20	34.61
2016	25.03	1.18	7.10	7.38	1.20	34.79

MANAGEMENT PROCEDURES

MEASURES OF FISHING INTENSITY

Fishing intensity is a measure of how fishing is affecting the stock, and it is the management procedure in determining the scale of the current harvest policy shown in Figure 1. An intuitive measure of fishing intensity is an exploitation rate, which is simply the catch divided by the exploitable biomass. Less intuitive, but similar, is instantaneous fishing mortality, which is used in an exponential function, as is M. These are obvious measures of fishing intensity for a single fleet, but become very complicated when considering multiple fleets with different selectivities or annual changes in selectivity.

Measures of fishing intensity have been developed that are more holistic and provide a meaningful measure of fishing effort on the stock of fish, rather than a specific portion. Many of these metrics focus on the effect of fishing on the spawning biomass, and often measure the long-term effects after fishing consistently at the same intensity. The following are some of the desired properties of a fishing intensity metric (many from pers. comm., Owen Hamel, NWFSC).

- As fishing effort increases, the fishing intensity metric also increases appropriately.
- Applies to simple as well as complex (i.e., multiple areas and fleets) models.
- Metric changes with changes in selectivity, and captures systematic changes in selectivity.
- Easy to compute.
- A scale that is easy to understand.

A commonly used metric is the spawning potential ratio (SPR), which is a measure of the effect of fishing on the long-term reproductive potential of the stock. This metric is currently used in the IPHC interim harvest policy. Potential metrics to consider for evaluation are listed below along with descriptions. Table 3 compares the metrics.

U (exploitation rate): catch divided by a summary biomass (which may or may not be exploitable biomass). This metric ignores differences between fisheries and their impacts of different ages, sizes, and sexes. Changes in selectivity will not be captured by U unless selectivity is specifically defined in the summary biomass (as with exploitable biomass). Overall, this is not a useful metric when there is more than one fishery.

F (instantaneous fishing mortality): a measure of the fishing mortality on the most highly selected age, size, and sex. Catch is a function of F and selectivity, and a change in selectivity results in a change to the meaning of F. The scale of F is also not easily interpretable. Overall, this is a useful measure of fishing mortality for modelling, but is not as useful as a metric.

SPR (spawning potential ratio): a measure of the effect of fishing on the long-term reproductive potential of the stock. More specifically, it is the percentage of long-term, equilibrium spawning output-per-recruit when fishing at a constant fishing intensity (F_{SPR}), divided by the long-term, equilibrium spawning output-per-recruit without fishing. Spawning output for Pacific halibut is measured by spawning biomass. The higher the fishing intensity (F_{SPR}), the lower the SPR (Figure 3). For example, SPR=100% is, by definition, no fishing; and SPR=40% is a fishing level that reduces the equilibrium spawners-per-recruit (i.e., spawning potential) to 40% of the unfished level. The general equation for SPR is

$$SPR = \frac{\widetilde{SB}_F / R_F}{\widetilde{SB}_{noF} / R_{noF}} \qquad (1)$$

where $\widetilde{SB}$ is the spawning biomass simulated forward to equilibrium with fishing (*F*) or without fishing (*noF*), and *R* is recruitment.

SPR, in general, is slightly different than simply dividing equilibrium spawning biomass when fishing by unfished equilibrium spawning biomass because SPR is on a per-recruit basis, thus eliminating the density-dependent effects of the spawner-recruit curve and simply measuring equilibrium spawning potential (see a comparison in Figure 5). In other words, SPR is the relative spawning potential of a recruit when faced with natural and fishing mortalities. SPR-based harvest policies are commonly used in the management of many fisheries around the world, including fisheries under U.S. fishery management council jurisdiction. An $F_{SPR=46\%}$ policy is currently the interim harvest policy at IPHC. Clark (1993) recommended that a $F_{SPR=40\%}$ for groundfish fisheries would maintain a high average yield.

To calculate SPR, the biology of the species (e.g., natural mortality, maturity, etc.), the selectivity for each fishery, and an overall fishing intensity (or fishing intensities for each fishery) are needed. The calculation of SPR always uses the biology and selectivities in the year of interest, thus accounts for changes in these parameters. However, an appropriate SPR for management should be robust to these changes.

This calculation of SPR is called static %SPR by Mace et al. (1996), and we will simply refer to it as SPR. Mace et al (1996) also presented the concept of "transitional SPR", which looks at the impact of fishing on existing cohorts in the stock (those that were present back in time) and thus is more of a retrospective measure, rather than quantifying current or future impacts. We do not consider transitional SPR metrics because those metrics are better suited to determine the level at which a stock has been fished, rather than providing a metric of how the stock is to be fished. The static %SPR (from now on simply called SPR) provides a measure of SPR given the current biological regime, fishery patterns, and a fishing intensity (F_{SPR}). See Mace et al. (1996) for further discussion of the difficulties calculating transitional SPR.

The metrics SPR and F_{SPR} has been reported in previous Pacific halibut assessments and are commonly calculated in many stock assessments around the world. It is a useful metric because it accounts for complex and temporally changing population dynamics and selectivities. It can be thought of as a measure of the spawning potential given fishing under the current conditions.

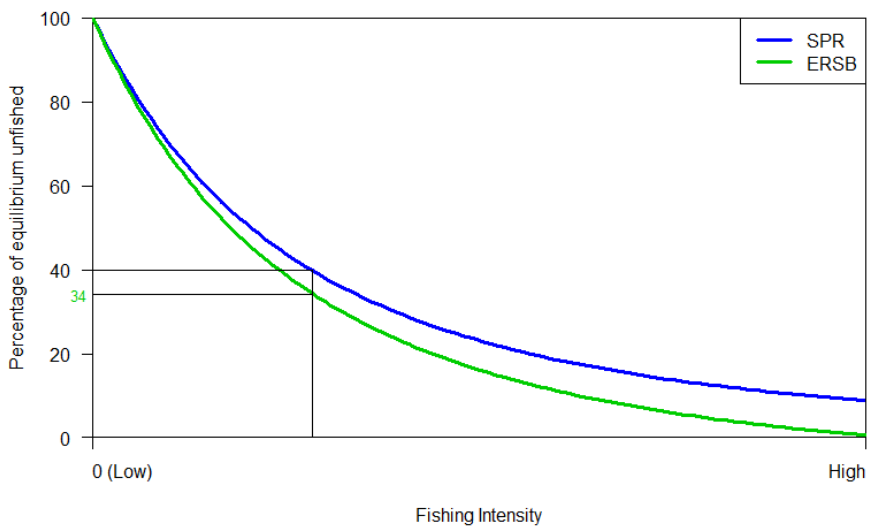

Figure 5: SPR and ERSB plotted against fishing intensity for a generic equilibrium model with constant recruitment (unweighted SPR) and time-invariant biology and selectivity.

ERSB (Equilibrium Relative Spawning Biomass): the long-term equilibrium relative spawning biomass given a level of fishing. Relative spawning biomass is the percentage of equilibrium spawning biomass with fishing ($F_{XX\%}$) relative to that without fishing. This was called ESD, or Equilibrium Stock Depletion, by Cordue (2012), but the term relative spawning biomass is used at the IPHC instead of depletion. The calculation is simply the equilibrium spawning biomass when fishing divided by unfished equilibrium spawning biomass. The calculation uses constant recruitment, and accounts for density-dependence of the stock-recruit relationship. In other words, this is the effect of fishing on the deterministic spawning potential of the stock, which reflects the decline in recruitment as the spawning biomass declines.

$$ERSB = \frac{\widetilde{SB}_F}{\widetilde{SB}_{noF}}$$

where $\widetilde{SB}$ is the spawning biomass simulated forward to equilibrium with fishing (*F*) or without fishing (*noF*). The only difference from SPR is the division by the number of recruits, and ERSB can be easily calculated from SPR using the following equation (with a Beverton-Holt stock-recruit relationship).

$$ERSB = \frac{4hSPR + h - 1}{5h - 1} \tag{2}$$

where *h* is steepness in the Beverton-Holt stock-recruit relationship. Notice that when steepness is equal to one (constant recruitment at all spawning stock sizes), ERSB is equal to SPR.

As with SPR, when temporal trends are present, the biology and selectivity used when calculating ERSB can affect the outcome. It is proposed to use the current conditions and project forward to determine the equilibrium spawning biomass with and without fishing. This keeps ERSB consistent with SPR and maintains the relationship in Equation (2). However, SPR and ERSB are similar metrics that can be calculated from one another, thus only one should be used for setting fishing intensity. RSB is currently used in the 30:20 control rule of the harvest policy, which may be a useful place in the harvest policy to use ERSB as a translation of the SPR value to a target RSB. However, RSB is slightly different than ERSB because the denominator in RSB is consistently B_0, which does not consider current biological conditions (but defined equilibrium conditions) when calculating. We'll discuss this more in the Control Rule section below.

FR (Fishing Ratio): the ratio of the biomass of fish that die due to fishing to the biomass of fish that die due to natural causes. This is not an equilibrium metric, but provides an insight into the current effect of fishing on the stock. This metric may be useful to gauge recent or current impacts due to fishing, but is not as useful for long-term management and strategic thinking. It could be used, for example, to set a maximum annual impact on the stock.

SER (Spawning Exploitation Rate): a measure of the reduction in spawning biomass due to fishing at a certain level, and was also termed "Annual Foregone Reproduction" by Mace et al. (1996). This metric was suggested by the SRB (at SRB09) and is calculated as $1\text{-}(SB_{\text{fishing},y}/SB_{\text{noFishing},y})$, where *SB* indicates spawning biomass and *y* is the year. This metric ranges from 0 to 1, with higher values indicating higher fishing intensity. It is not an equilibrium metric and does not specifically account for the mortality of smaller, immature fish. A target value will take into account the selectivity patterns of the fisheries, but it may be sensitive to shifts in selectivity. Overall, this metric is similar to SPR except that it is based on the immediate term rather than long-term equilibrium calculations. It may be an interesting metric to report annually, regardless of the fishing metric used to define the scale.

RFY (Relative Foregone Yield): this is the equilibrium yield calculated using current conditions and fishing intensity divided by the maximum equilibrium yield under current conditions. It provides a measure of the percentage of MSY, which can be related to "Pretty Good Yield" (Hilborn 2010). More thought needs to be given to this metric, but it is likely not a useful metric to determine fishing intensity mainly because there are two sides to the yield curve, and being at a percentage of MSY could mean that the stock is larger than expected at MSY or smaller than expected at MSY. It may be a useful metric to report and monitor, or to use in evaluations of different management procedures.

Table 5: A comparison of the different fishing intensity metrics.

Metric	Name	Multiple fisheries and areas	Equilibrium	Easy to calculate	Easy to interpret	Range	Account for all fishing mortality on all sizes	Current conditons or regime	Use?
U	Exploitation Rate	No	No	Yes	Yes	0–100%	No	Possibly	Leave to modelling
F	Instantaneous Fishing Mortality	No	No	Yes	No	0–∞	No	Yes	
SPR	Spawning Potential Ratio	Yes	Yes	Yes	Yes	0–100%	Yes	Yes	For Fishing Intensity
ERSB	Equilibrium Relative Spawning Biomass	Yes	Yes	Yes	Yes	0–>100%	Yes	Possibly (dynamic?)	For Control Rule
FR	Fishing Ratio	Yes	No	Yes	Yes	0–∞	Yes	Yes	Report or use as a Performance Metric
SER	Spawning Exploitation Rate	Yes	No	Yes	Yes	0–100%	Yes	Yes	
RFY	Relative Foregone Yield	Yes	Yes	Yes	Ues	0–100%	Yes	Yes	

CONTROL RULE

The control rule is an additional part of the harvest policy that affects the fishing intensity or FCEY. The premise of a control rule is that if the stock declines below a threshold reference point (typically measured in relative spawning biomass) the fishing intensity is reduced, and if the stock declines below a limit reference point there is no harvest. This is used to avoid low stock sizes by acting in a precautionary manner when the stock size begins to approach the limit. The current IPHC control rule is called a 30:20 rule because the threshold is 30% RSB and the limit is 20% RSB (Figure 4).

The multiplier can act on the fishing level (i.e., fishing intensity) or the catch (i.e., FCEY), and it would be somewhat straightforward for the fishing intensity to be adjusted. For example, if $F_{SPR=46\%}$was the fishing intensity, the F could be adjusted, or the SPR could be adjusted. The relationship between SPR and FI is nonlinear (Figure 3) thus a linear adjustment to one would result in a nonlinear adjustment to the other.

Adjusting the catch may be more difficult because there are portions of the catch that are not directly controlled by the IPHC. It would be possible to adjust the FCEY, but the other components of the TCEY as well as the U26 mortality would not be adjusted. This also brings up an important point about adjusting the FI. The FI defines the total mortality, some of which is not controlled by the IPHC, therefore the FI would not decline to zero when below the limit threshold unless cross-agency management measures were agreed upon.

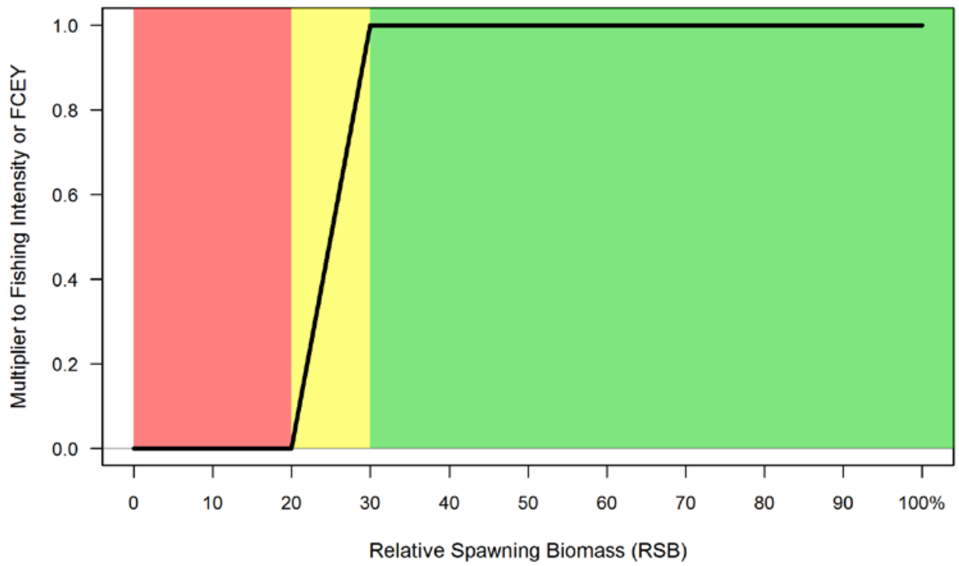

Figure 6: Control rule for the IPHC harvest policy. It is commonly called a 30:20 control rule because the downward adjustment begins at a relative spawning biomass (RSB) of 30% (threshold reference point) and no harvest occurs when the RSB is below 20% (limit reference point). The adjustment has been made to the harvest rates in the past, but the adjustment may be made to the fishing intensity or to the FCEY.

The current IPHC assessment used RSB to determine stock status with a static unfished equilibrium biomass (B_0), calculated assuming good size-at-age and poor recruitment, as the reference. This static definition has many potential problems. First, it is not necessarily reflective of current conditions. Second, if fishing were to stop and current conditions remained constant, the RSB would not go to one, but could be less than or greater than one. Lastly, a change in conditions could potentially result in a RSB below the threshold even without fishing. In some cases a specific static reference point may be the desired target, but not accounting for current conditions may be misleading when managing a dynamic stock subject to changing conditions.

We propose to use SPR to define fishing intensity, which is an equilibrium concept using current conditions. When a target SPR is defined, a target ERSB is also defined (assuming the Beverton-Holt stock-recruit curve and a value for steepness). With a target related to stock status one may also define a threshold and limit in relation to that target (Figure 7). However, the x-axis of the control (stock status) should also be based on current conditions instead of a static definition.

A dynamic quantity to define current stock status would be consistent with SPR and ERSB and could be used to determine at what stock status fishing intensity is reduced. We suggest that the current status have the property that if fishing had not occurred over the last generation, then the calculation of this quantity would result in a value of one. In other words, the current status would be a measure of the effect of fishing and does not include the effect of changing conditions or recent deviations in recruitment. Dynamic B_0 (McCall et al. 1985) is a dynamic calculation of stock status that uses the conditions and recruitment deviations that the stock has recently experienced. It also corrects for the reduction in average recruitment due to the stock-recruit function. This quantity has also been called ????? and used in tuna assessments (REF).

Using SPR and translating that to ERSB results in consistent equilibrium quantities for fishing intensity and target stock status. Dynamic B_0 is the consistent link to determine the current fishing effect on stock status, which we call dynamic RSB (dRSB). Using these three quantities provides for a control rule where each component relates to each other in a meaningful way. For example, a stock would be expected to fluctuate around a target ERSB due to natural variability in recruitment. It is likely that dropping below the threshold is not a highly desired state due to a curtailing of fishing effort, and if the threshold was near the target, it would be crossed often due to variability in the population. Setting the threshold less than the target reduces the probability of curtailing fishing effort and builds the stock back to expected levels when the current stock status is lower than desired. However, if the desire is to build back to the target as quickly as possible, a threshold closer to the target may be useful.

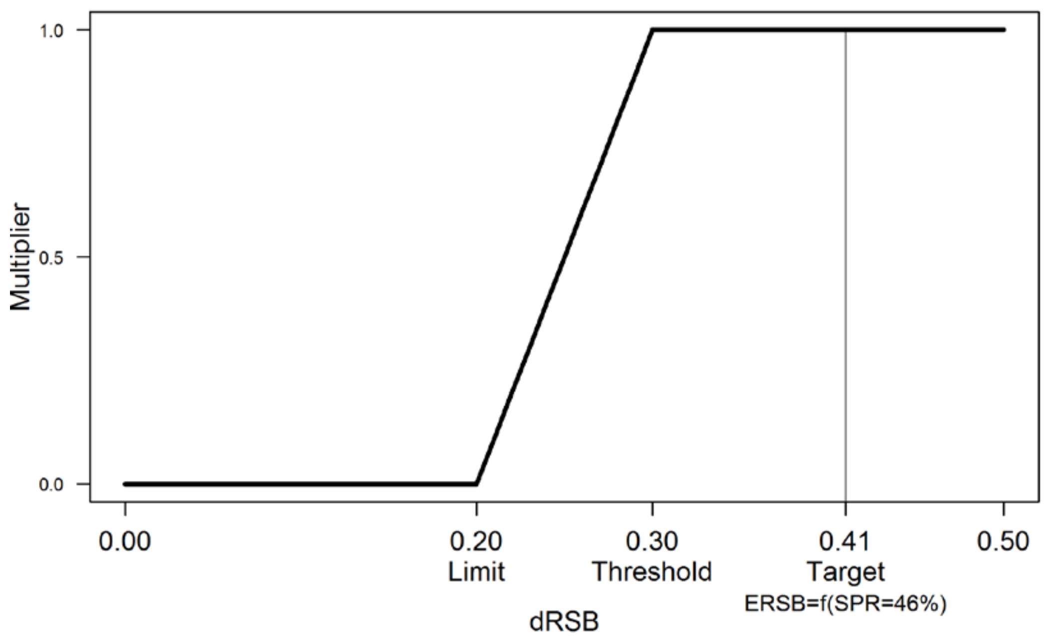

Figure 7: Components of the control rule.

A concern may be that in extreme cases where non-fishing related influences result in a static stock status below a threshold, the dynamic approach would not reduce the fishing intensity appropriately to maintain a minimum spawning biomass. Using SPR to define a fishing intensity helps to alleviate this concern since it determines a relative spawning potential. Even though SPR is based on current conditions, it still maintains a minimum spawning potential.

A consistency between reference points is useful because it helps to relate the different components of the control rule to each other and define meaningful values. The control rule is part of the harvest strategy determining the scale of fishing and we plan to evaluate various components in the 2017 MSE. The MSAB decided to test a 30:20 control rule and a 40:20 control rule using dRSB. We will use our best judgment to determine if other thresholds and limits would be useful to evaluate at this time.

RECOMMENDATION/S

That the SRB:

1) **NOTE** paper IPHC-2017-SRB10-09 which provided an overview of the simulations to evaluate the fishing intensity and harvest control rules in the IPHC Harvest Strategy Policy.
2) **CONSIDER** the simulation framework and assumptions as described, including scenarios and distribution of the TCEY.
3) **CONSIDER** fishing intensity metrics and associated levels to evaluate, NOTING that the IPHC Secretariat suggests only evaluating SPR-based fishing intensity metrics and using other metrics as evaluation tools (i.e. performance metrics) or as components of the control rule (e.g. ERSB).
4) **CONSIDER** control rules to evaluate, including threshold (trigger) and limit reference points, as well as what the control rule adjusts. Discuss the shape of the control rule and whether the multiplier is zero when below the limit reference point.
5) **CONSIDER** the use of dRSB for stock status in the control rule and its relation to ERSB and SPR.

ADDITIONAL DOCUMENTATION / REFERENCES

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APPENDIX A: DEFINITIONS

Estimation Model (EM) is analogous to the stock assessment. Using the data generated, it produces an annual estimate of stock size and status and provides the advice for setting the catch levels for the next time step.

Fishing Intensity (FI): A measure of the total fishing mortality on all sizes and through all sources. An example is $F_{SPR=XX\%}$ which indicates a level of fishing that would result in an SPR of XX%.

Harvest Strategy Policy: collection of management procedures, including ones related to monitoring, the estimation model, and the harvest strategy, that guide harvest recommendations. In addition, it includes the final decision making process of the Commissioners.

Harvest Strategy the procedure that uses data and the estimation model output to produce the catch limit (TCEY) for that year.

Management Strategy: collection of management procedures, including ones related to monitoring, the estimation model and the harvest strategy, that guide harvest recommendations. This is a strategy that can be written down and does not involve Commissioner decisions and negotiations.

Management Procedure: a specific component of the management strategy (e.g., Fspr).

Monitoring (data generation) is the code that simulates the data from the operating model that is used by the estimation model. It can introduce variability, bias, and any other properties that are desired.

Operating Model (OM): a representation of the population and the fishery. It produces the numbers-at-age, accounting for mortality and any other important processes, and also incorporates uncertainty in the processes.

Relative Spawning Biomass (RSB): The current spawning biomass divided by a static reference spawning biomss (e.g., B_0).

Scenario: A set of assumptions that we cannot or choose not to control. For example, the value of natural mortality used in the operating model.

Spawning Potential Ratio (SPR): A commonly used metric of fishing intensity. SPR is the ratio of the equilibrium spawning biomass per recruit given some level of fishing and the equilibrium spawning biomass per recruit in the absence of fishing. An SPR equal to 100% implies no fishing, and lower SPR values indicate higher fishing intensities.

Total Constant Exploitation Yield (TCEY): The amount of yield of halibut greater than 26 inches in length from all sources.