A quantitative tool for evaluating rebuilding plans for Pacific salmon

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by

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ABSTRACT

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Rebuilding plans are required for depleted stocks under the Fish Stock Provisions of Canada's revised Fisheries Act (2019) and DFO's Sustainable Fisheries Framework (2009). The overall goal of this project was to create a tool for developing and evaluating the harvest component of rebuilding plans for Pacific salmon, which evaluates trade-offs between conservation objectives and other fisheries management objectives. This rebuilding tool, called `samSim` can be used to explore performance of candidate rebuilding harvest strategies in the context of multiple mixed-stock fisheries and environmental forcing of population dynamics that may impact productivity and confound recovery efforts. `samSim` was scoped to focus on harvest actions before more detailed strategies that integrate multiple management interventions (e.g., habitat and hatcheries) can be developed to support rebuilding. The outcomes from this project are intended to form a possible first step towards an integrated rebuilding plan that includes First Nations and stakeholders. In this first phase, we applied the `samSim` to two case studies: Fraser Rivers sockeye salmon, a data-rich example, and Nass River chum salmon, which was relatively data limited. `samSim` can be expanded in future phases within a broader simulation framework and context of multiple stressors. The tool, `samSim`, is freely accessible and documented in a public repository online.

RÉSUMÉ

Holt, C.A., Freshwater, C., Holt, K., and Huang, A.-M. 2020. A quantitative tool for evaluating rebuilding plans for Pacific salmon. Can. Tech. Rep. Fish. Aquat. Sci. 3402: v + 26 p.

Des plans de rétablissement sont requis en raison des stocks épuisés en vertu des dispositions sur les stocks de poissons de la version révisée de la Loi sur les pêches du Canada (2019) et du Cadre pour la pêche durable du MPO (2009). L'objectif global de ce projet était de créer un outil pour l'élaboration et l'évaluation du volet pêche des plans de rétablissement du saumon du Pacifique, qui évalue les compromis entre les objectifs de conservation et les autres objectifs de gestion des pêches. Cet outil de rétablissement, appelé `samSim`, peut être utilisé pour explorer la performance des stratégies étudiées de reconstitution des stocks dans le contexte de multiples pêches de stocks mixtes et du forçage environnemental de la dynamique des populations qui peuvent avoir une incidence sur la productivité et brouiller les efforts de rétablissement. L'outil `samSim` a été conçu pour mettre l'accent sur les mesures de récolte avant que des stratégies plus détaillées qui intègrent de multiples interventions de gestion (p. ex., habitat et écloseries) puissent être élaborées pour appuyer le rétablissement. Les résultats de ce projet visent à constituer une première étape possible vers un plan de rétablissement intégré qui inclut les Premières Nations et les intervenants. Dans cette première phase, nous avons appliqué `samSim` à deux études de cas : le saumon rouge du fleuve Fraser, un exemple riche en données, et le saumon kéta de la rivière Nass, qui était relativement limité en données. L'outil `samSim` peut être étendu dans les phases futures dans un cadre de simulation élargi et dans un contexte de facteurs de stress multiples. L'outil `samSim` est accessible librement et documenté dans un dépôt public en ligne.

1 Introduction

There are approximately 460 Conservation Units (CUs) of Pacific salmon, of which a significant proportion have been assessed or are expected to be assessed with poor status below conservation thresholds. Rebuilding plans are now required for major stocks (aggregates of CUs that are managed together) that drop below limit reference points under the revised Fisheries Act (DFO 2019a). In addition, Canada's Wild Salmon Policy specifies that actions should be considered to rebuild CUs when they drop below lower biological benchmarks. However, progress on developing rebuilding plans has been limited, in part because of a lack of tools to identify and evaluate management actions for depleted CUs. Once identified, fisheries managers face the additional challenge of identifying how to best achieve CU-specific targets within multiple mixed-CU fisheries.

Our overall goal was to create a simulation tool to inform the development and evaluation of harvest components of rebuilding plans for Pacific salmon, which evaluates trade-offs between conservation objectives and other fisheries management objectives. In the first phase of this project, we developed a prototype of the tool to evaluate the extent to which reductions in harvest impact rebuilding potential, if at all, and explore how to achieve rebuilding targets in the context of multiple mixed-stock fisheries. In addition, we considered environmental forcing of population dynamics that may impact productivity and confound recovery efforts. The rebuilding tool was scoped to focus on harvest actions before more detailed strategies that integrate multiple management interventions (e.g., habitat and hatcheries) can be developed to support rebuilding. The outcomes from this project are intended to form the first step in the development of an integrated rebuilding plan that includes engagement with First Nations and stakeholders. We applied the prototype to two case studies, a data-rich and data-poor example, which can be expanded in future phases within a broader simulation framework and context of multiple stressors (Management Strategy Evaluation, MSE).

1.1 Policy Context

DFO's Fisheries Decision-Making Framework Incorporating the Precautionary Approach (Precautionary Approach Framework DFO (2009)) provides guidance on how to manage fisheries in a precautionary manner. This framework states that "when a stock has reached the Critical Zone, a rebuilding plan must be in place with the aim of having a high probability of the stock growing out of the Critical Zone within a reasonable timeframe". Further direction is provided in DFO's "Guidance for the Development of Rebuilding Plans under the Precautionary Approach Framework: Growing Stocks out of the Critical Zone" (Guidance on Rebuilding), an annex of the Precautionary Approach Framework. This guidance document recommends the development of simulation models within the context of Management Strategy Evaluations (MSEs) to examine the consequences of alternative management measures aimed at rebuilding depleted stocks under different plausible hypotheses about uncertain population and fisheries dynamics. It states that transparency in responding to trade-offs among objectives (e.g., conservation and socio-economic) is essential for effective decision making, and that MSE can aid in building in stronger relationships among DFO, First Nations, and stakeholders, fostering open and transparent decision making. Given expectations from First Nations for increased collaboration and involvement in decision-making, MSE may provide a platform for this engagement.

The revised Fisheries Act (DFO 2019a) further requires the development and implementation of rebuilding plans for major stocks that fall below limit reference points. Although rebuilding plans will be developed at the scale of stock management units for Pacific salmon, these need to consider the conservation of diversity at the scale of CUs. Guidance on developing rebuilding plans under the Fisheries Act is currently in development.

In addition, the Wild Salmon Policy (WSP) aims to restore and protect healthy and diverse salmon CUs and their habitats, where diversity of Pacific salmon is protected, in part, through preserving CUs. A significant portion of the approximately 460 CUs of Pacific salmon have been assessed, or are expected to be assessed, with poor status below conservation thresholds (below lower benchmarks resulting in status in the "red zone"). The WSP (DFO 2005) states,

> *A CU in the red zone is undesirable because of the risk of extirpation and the loss of ecological benefits and salmon production. The presence of a CU in the red zone will initiate an immediate consideration of ways to protect the fish, increase their abundance and reduce the risk of loss. Biological considerations will be the primary driver for the management of CUs with red status.*

The WSP also states that sustainable use and managing fisheries for sustainable benefits are important considerations for managing CUs. Accordingly, rebuilding efforts will need to consider social and economic impacts as well as conservation objectives. Trade-offs among conservation and short- and long-term social and economic objectives should be made in a clear and transparent manner. Indeed, the fourth principle of the WSP requires that decision-making be transparent and inclusive.

The 2018 Implementation Plan for the WSP identified a gap between DFO's current response to depleted CUs and that required in the WSP (DFO 2018). The Implementation Plan includes the development of long-term strategic plans for rebuilding priority CUs or management units (aggregates of CUs). However, progress on implementing rebuilding strategies within Integrated Fisheries Management Plans or other processes has been limited, in part due to a lack of quantitative tools to evaluate alternative harvest strategies proposed within rebuilding plans.

Furthermore, the Committee on the Status of Endangered Wildlife in Canada, COSEWIC has assessed 10 Fraser River Sockeye Salmon Designatable Units (DUs, the unit of conservation identified by COSEWIC), 12 Southern BC Chinook Salmon DUs, and 1 Interior Fraser Coho Salmon DU as threatened or endangered. Recovery Potential Assessments have been or are being developed for these DUs, which include forward projection tools that demonstrate the recovery potential of current and alternative mortality rates. However, those models typically lack sufficiently detailed harvest strategies to provide realistic guidance to managers about harvest options. The primary goal of Recovery Potential Assessments is to identify the overall potential for recovery and not to evaluate trade-offs among harvest control rules in their performance against multiple objectives.

The significant impacts of climate and environmental conditions on fish stocks are recognized in DFO's Guidance on Rebuilding, which states that, "the influence of environmental conditions on rebuilding should be considered and incorporated into rebuilding efforts for depleted stocks". To inform these rebuilding efforts, DFO has developed a National Working Group on an Ecosystem Approach to Fisheries Management. More broadly, the ability to achieve management goals is impacted by climate and environmental variability and international best practices include the development of simulation tools to evaluate management strategies under a range of plausible hypotheses about climate impacts (Punt et al. 2014; King et al. 2015).

The proposed tool fills these some of these gaps by evaluating trade-offs among conservation and harvest objectives for candidate harvest control rules of Pacific salmon, including those within mixed-CU fisheries containing weak and productive CUs, and considering various future scenarios for climate and environmental conditions.

2 Quantitative Tool for Evaluating Rebuilding

2.1 Feedback simulations

Fisheries management is frequently tasked with implementing strategies that meet multiple, and often conflicting, broad objectives while remaining robust to sources of uncertainty. Management strategy evaluation (MSE) is a decision-making framework that allows scientists, managers, First Nations, and stakeholders to collaboratively develop and test alternative management procedures in a controlled and low-risk environment. In the MSE framework a management procedure is the combination of (i) a data collection scheme, (ii) a method of assessing CU status, and (iii) management actions based on estimated CU status (i.e., harvest control rules). The MSE process begins with the identification of fully-specified objectives (e.g., time to and probability of reaching specific recovery targets and harvest goals) and the design of management procedures that could realistically be implemented to meet those objectives.

Once objectives and performance indicators have been identified, feedback (or closed-loop) simulations are used to apply and evaluate different management procedures. In these simulations, real-world CUs and fisheries are replaced by a series of models that represent several distinct processes: the dynamics of fish populations, observations of these populations, and the behaviour of the fishery. Together these models constitute an operating model that represents one or more hypotheses about how the “true” system could behave. Importantly, these models include feedback from the impacts of management actions in a given year on the population size in the following year. The operating model is initially parameterized with historical data or representative values drawn from previous studies. When social, cultural, or institutional objectives cannot be fully specified within feedback simulations, these objectives should be considered in the broader evaluation of management strategies (Stephenson et al. 2017; Armitage et al. 2019).

A principal goal of this feedback simulation is to determine how robust distinct management procedures are to sources of uncertainty (e.g. form of stock-recruit relationships, precision of spawner abundance estimates, and implementation of harvest control rules). Multiple dimensions of uncertainty are incorporated into the simulation by designing several operating models, with each model containing unique combinations of parameter values and underlying model structures that represents a specific hypothesis about the system’s behaviour. Different management procedures are then applied to each operating model creating a suite of unique scenarios (each scenario equals one operating model and one management procedure). Every scenario is then iterated across many time steps to incorporate stochasticity and explore how the system is likely to behave in the future (Figure 1). Finally, management procedures are evaluated relative to one another based on their mean performance across many trials. By comparing how management procedures perform across multiple operating models, the simulation tool allows managers and stakeholders to assess trade-offs between exploitation/yield and conservation objectives under varying degrees of uncertainty.

Although technically complex, feedback or "closed-loop" simulation models can be broken down into relatively simple components, including stock dynamics, collection of spawner and harvest data, assessment of status, application of harvest control rules, and implementation of a fishery (1). The quantitative model described here can become an important component of future MSE processes that would be developed in collaboration with First Nations and stakeholders. The structure of the model is described in more detail below. These models are of little use without quantitative and realistic goals (e.g., those related to rebulding) that are actually relevant to management, and that can be used to assess the performance of management procedures. Ideally, these goals should include three components: a threshold representing CU status (e.g. a level of spawner abundance), a specified probability of reaching or avoiding the threshold, and a minimum/maximum number of years to reach the threshold. The Appendix includes a list of candidate objectives, performance metrics, and thresholds that can be evaluated with this simulation model.

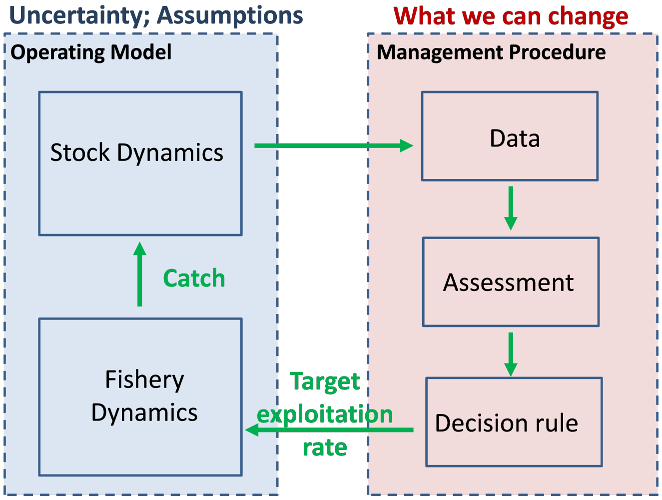

Figure 1. Schematic of closed-loop simulation within Management Strategy Evaluation.

For this project, the overall goals of the simulation evaluation were identified through engagement with Fisheries Management at an initial Workshop in December 2017. These goals represented four different components and to date our efforts have focused on the first three. Preliminary results on the fourth are presented with additional recommendations for further work. Parentheses highlight the associated case study and published outputs which provide a more thorough description of the results. An overview of results are provided here.

1. Evaluate impact of candidate harvest strategies on rebuilding (Case Study 1: Fraser River sockeye salmon, Freshwater et al. (2019); Freshwater et al. (2020))

2. Evaluate the impact of uncertainty in productivity and associated trends on rebuilding (Case Study 1, Freshwater et al. (2019); Freshwater et al. (2020)).
3. Evaluate impacts of combinations of mixed and single-stock fisheries on rebuilding (Case Study 1, Freshwater et al. (2019)).
4. Evaluate the impacts of uncertainties in assessment (changes in frequency and intensity of assessment) and from implementing management strategies (outcome uncertainties) on rebuilding and our ability to detect recovery. (Case Study 2: Nass River chum salmon)

We initially compiled a longer list of management questions and biological and assessment uncertainties to consider in more depth, which formed additional modules of the simulation model. These were narrowed to the list of four goals (or modules) above. The Appendix includes a complete list of modules considered.

2.2 samSim- A Generic Simulation tool

`samSim` is an R package containing functions to quantify the rebuilding potential for Pacific salmon populations. Within `samSim`, the primary function controlling the closed-loop simulation routine is named `recoverySim`. The model structure focuses on aggregates of salmon conservation units (CUs), the focal unit for assessing Pacific salmon status in Canada (DFO 2005). Generally all CUs included within a single analysis should be managed simultaneously as a management unit (MU); however, the model can be adapted to include multiple MUs with distinct harvest rates. Although initial case studies focused on Fraser River sockeye salmon and Nass River (Area 3) chum salmon, `samSim` is intended to be applicable to any Pacific salmon species as long as two requirements are met. First, CU-specific stock-recruit parameters and age-at-maturity values must be available to parameterize the operating model. These values can either be derived from observed, CU-specific time series of age-structured spawner and recruit abundance or can be estimated using alternative techniques (e.g. habitat-based models; expert opinion). Second, harvest of immature fish must be considered negligible because offshore fisheries and/or stock distributions that remain in nearshore waters (and thus vulnerable to fisheries) throughout their lifecycle are not accounted for in the model. The code for `samSim` is available on GitHub at `https://github.com/Pacific-salmon-assess/samSim`.

`recoverySim` uses observed time series of spawner abundance to prime the simulation so that each CU's initial status reflects the most recent assessment. Those abundances, along with externally estimated stock-recruit parameters, are used as inputs to a Ricker model (Larkin models can also be used for cyclic CUs) that generates a cohort of *recruits* (i.e. the total number of adult offspring produced by a given brood year of spawners). This process is stochastic, incorporating interannual variation in recruitment deviations, as well as covariance among CUs and temporal autocorrelation. Age-at-maturity varies among simulated recruits based on input parameters and multivariate logistic distribution. This process creates cohorts of *returns*, the total number of adult offspring returning to spawn in a given year, which consist of mature fish of various ages and brood years.

Simulated returns may next be harvested by up to three discrete fisheries. The first fishery represents American harvest, which typically occurs during return migrations before Canadian

CUs enter nearshore areas. American catches are always generated using a fixed exploitation rate that is passed as an input value. The second fishery represents Canadian mixed-CU harvest. Catch rates here are determined by one of three harvest control rules (HCRs): fixed exploitation rate, generic abundance-based, or total allowable mortality (TAM). The generic abundance-based HCR increases exploitation rates from a minimum value when return abundance exceeds user-specific reference points. The TAM rule is similar to the generic abundance-based HCR, but has additional modifications currently implemented in Fraser River sockeye salmon management (Pestal et al. 2011). The third fishery represents near-terminal, single-stock harvest. While American and mixed-stock Canadian HCRs are a function of MU abundance, single-stock harvest is driven by abundance at the CU scale. Single-stock harvest is modeled as a proportion (0-1) of the mixed-stock total allowable catch, with the additional option to close specific CU's fisheries based on recent or forecasted abundance (Freshwater et al. 2020). In each fishery, target catches (generated using the HCR) are converted to realized catches by incorporating stochastic outcome uncertainty (Holt and Peterman 2006). In mixed-stock fisheries, CU-specific realized catch is then calculated as a function of relative abundance. Once catch has been removed the remaining returns become spawners, creating the subsequent generation of recruits.

The simulation model produces a range of outputs automatically. A PDF of diagnostics contains simulated stock-recruit relationships, as well as time series of abundance, population parameters, and various performance metrics. Automatically generated R data and .csv files contain arrays of CU-specific time series, matrices of aggregate time series, and data frames of aggregate or CU-specific performance metrics. Each file contains all the Monte Carlo trials for a specific scenario.

The output files are used by additional `samSim` functions to create various summary figures. Each figures incorporates user-defined percentile intervals that are calculated across Monte Carlo trials to provide an estimate of uncertainty. The `plotContTradeoffs` function generates double-y axis line plots that demonstrate how spawner abundance, stock status, and extinction probability change as exploitation rates increase within a single scenario (Fig. 2). The `plotAgDot` and `plotCUDot` functions provide summaries of multiple performance metrics (aggregate or CU-specific, respectively) across different management procedures or different operating models. For example, we can visualize declines in return size and the proportion of CUs above their biological benchmark as exploitation rates increase, as well as how such patterns differ among two different productivity regimes (Fig. 3). The `plotAgTradeoff` and `plotCUTradeoff` functions plot a conservation metric on the x-axis and a catch metric on the y-axis to visualize how tradeoffs between objectives vary among management procedures or operating models. Such figures can be particularly useful in identifying subsets of management procedures that meet pre-specified objectives (e.g. minimum median return sizes and catches), while readily incorporating different operating models. For example, intermediate fixed exploitation rates or an abundance-based (TAM) harvest control rule may lead to optimal outcomes in a reference productivity scenario, but fail to meet threshold objectives when productivity is low (Fig. 4).

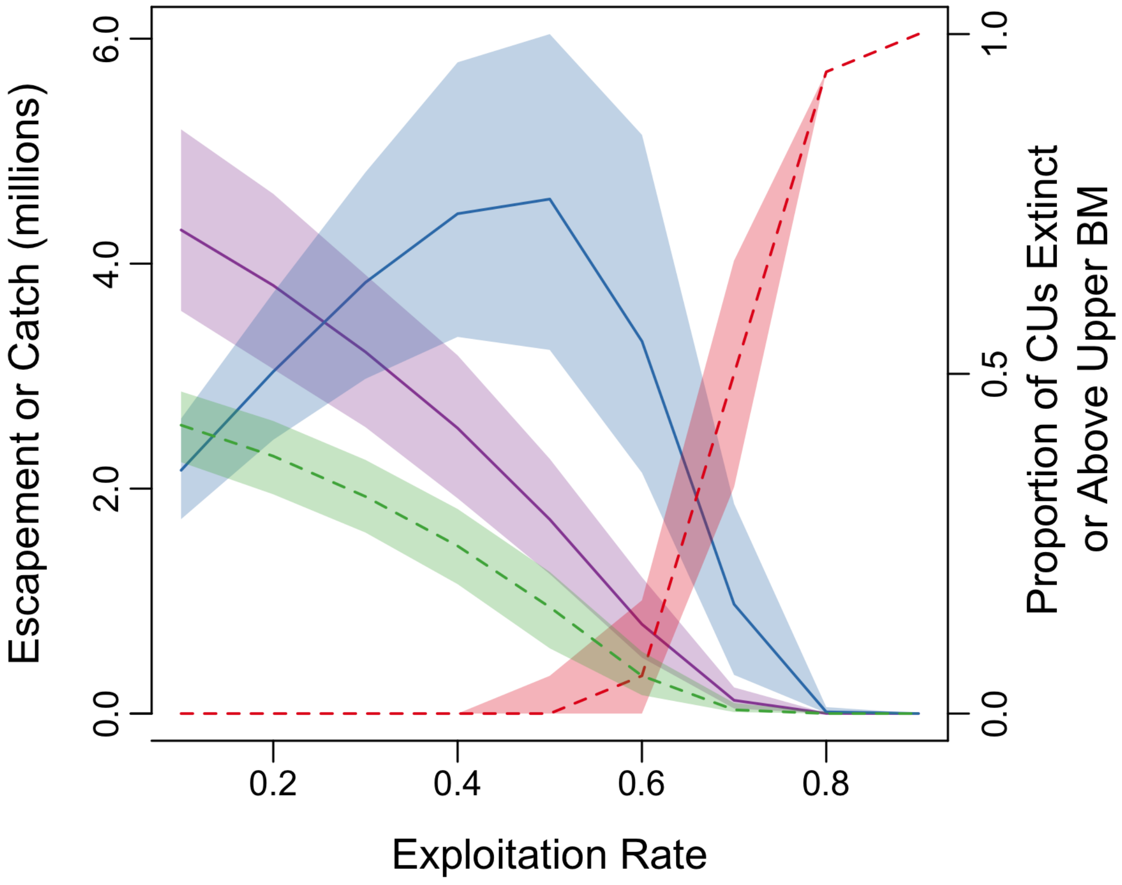

Figure 2. Changes in aggregate conservation- and catch-based performance metrics (escapement - purple; catch - blue; proportion of CUs above benchmark - green; extinction risk - red) as fixed exploitation rates increase. Dark lines represent median values and the shaded polygons the 90th percentile interval across Monte Carlo trials. Output of function: plotContTradeoffs()

2.3 Summary of Case Study on Fraser River sockeye salmon (Case Study 1)

We applied the quantitative tool first to a data-rich aggregate of 19 Fraser River sockeye salmon CUs to evaluate the impacts of various constant target exploitation rates and a “Total Allowable Mortality” (TAM) rule meant to represent a simplified version of the harvest control rule currently used for Fraser River sockeye salmon (see Freshwater et al. 2019 for details). We evaluated performance for aggregate spawner abundances against an arbitrary threshold of 3 million fish, and for aggregate catch against a threshold of 1 million fish, which approximates the minimum number required prior to opening Canadian commercial fisheries.

We found exploitation rates between 20 and 40% generally achieved both objectives, as did the TAM rule (Fig. 4). However, for several of the component CUs spawner abundances were below lower biological benchmarks in a relatively high proportion of years (>25%) under all of these management procedures (e.g., Harrison, Late Stuart, Quensel, and Raft in Fig. 5). Only a subset

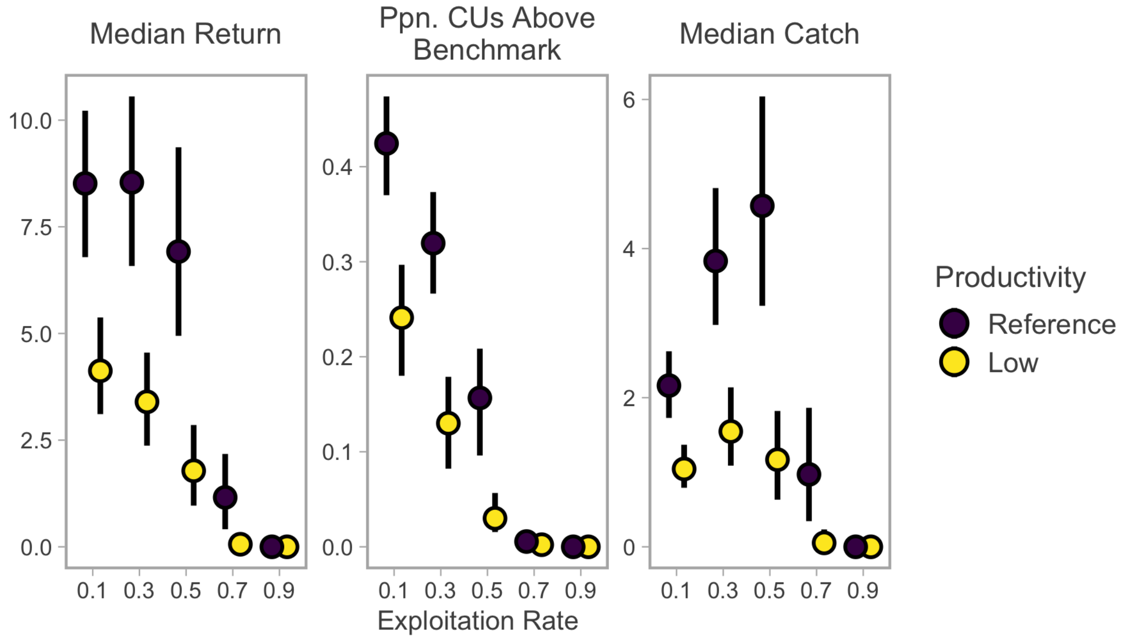

Figure 3. Performance across three metrics as a function of fixed exploitation rate (x-axis) and two productivity operating models (color). Points represent median values and whiskers the 90th percentile interval across Monte Carlo trials. Output of function: plotAgDot().

of the 19 CUs that have similar similar summer run-timing and are managed together, are shown here. Further discussion on trade-offs among objectives under different productivity and in-river mortality scenarios are documented in Freshwater et al. (2020, 2019).

2.4 Summary of Case Study on Nass River Chum Salmon (Case Study 2)

The objective of the Nass River (Area 3) Chum rebuilding plan is to “protect Area 3 wild Chum and at the same time provide opportunities to retain enhanced US Chum in places and times where they are most abundant” DFO (2019b). Canadian catch of Area 3-origin chum salmon occurs primarily as by-catch in the sockeye salmon fishery. The Canadian exploitation rate is currently capped at 10% to allow for rebuilding of depleted CUs. The Nass River contains three CUs: Lower Nass, Portland Canal-Observatory, and Portland Inlet.

Our goal was to evaluate the impacts of outcome uncertainty on probability of rebuilding for component CUs. Outcome uncertainties, sometimes refered to as management or implementation uncertainties, are deviations between target and realized catch rates intended to represent imperfect management in a real-world system (e.g. unreported catch, delays in HCR implementation). Our primary question was, to what extent does variability in realized exploitation rates, occasionally above the 10% cap, limit ability for CUs to rebuild? Outcome uncertainties were included in the model and parameterized using observed exploitation rates (including US exploitation), relative to the 10% limit. We further explored a wide range in outcome uncertainties, including a scenario with no outcome uncertainty. We found that when

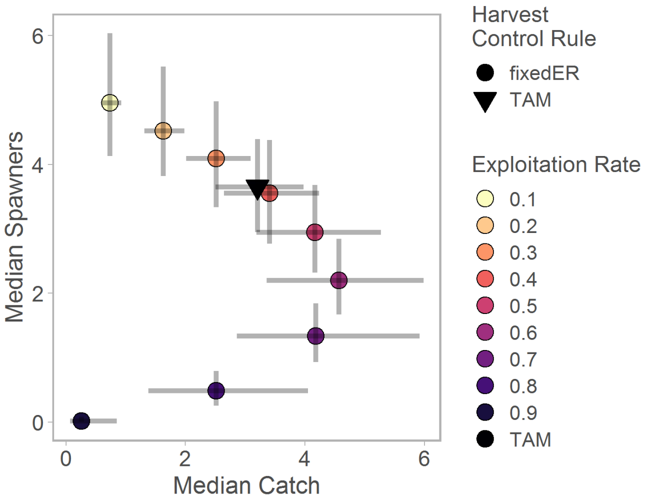

Figure 4. Trade-offs between aggregate catch and escapement for fixed exploitation rate and total allowable mortality harvest control rules. Points represent median values and whiskers the 90th percentile interval across Monte Carlo trials. Fixed exploitation rates, FixedER, are shown with circles and a Total allowable Mortality, TAM, rule is shown with an inverted triangle. Output of function: plotAgTradeoff().

multiple sources of uncertainty were considered in the operating model (e.g., natural variability in recruitment and age-at-maturity, alternative scenarios of productivity) and management procedure (e.g., observation errors), the relative impact of reducing outcome uncertainties was modest (Fig. 6). Although on average greater outcome uncertainty resulted in reduced spawner abundance and smaller catches over the long term because of intermittent overharvest, the additional sources of uncertainty (e.g., in productivity and population dynamics) tended to swamp signals from outcome uncertainties. Our results suggest that any reductions in outcome uncertainty would have minimal impacts on risks to rebuilding. In general, for data-limited stocks where uncertainties in population dyanmics are high, it is difficult to distinguish the performances of minor differences in management procedures.

3 Next Steps and Recommendations

Several potential additional model components were identified in collaboration with Fisheries Management at a Workshop April 2019 to better inform rebuilding plans under the Fisheries Act and the Wild Salmon Policy, and recovery strategies under the Species at Risk Act, SARA.

- The current modelling tool could be adapted to readily calculate and compare the time for rebuilding under pessimistic and optimistic harvest scenarios. These types of metrics have the potential to identify CUs for which harvest poses a high risk to rebuilding, as in the US by the National Marine Fisheries Service (NMFS) e.g., as described by Wetzel et al. (2016) and Benson et al. (2016). If the rebuilding times do not change with extreme harvest scenarios, then this would signal that rebuilding plans should focus on alternative

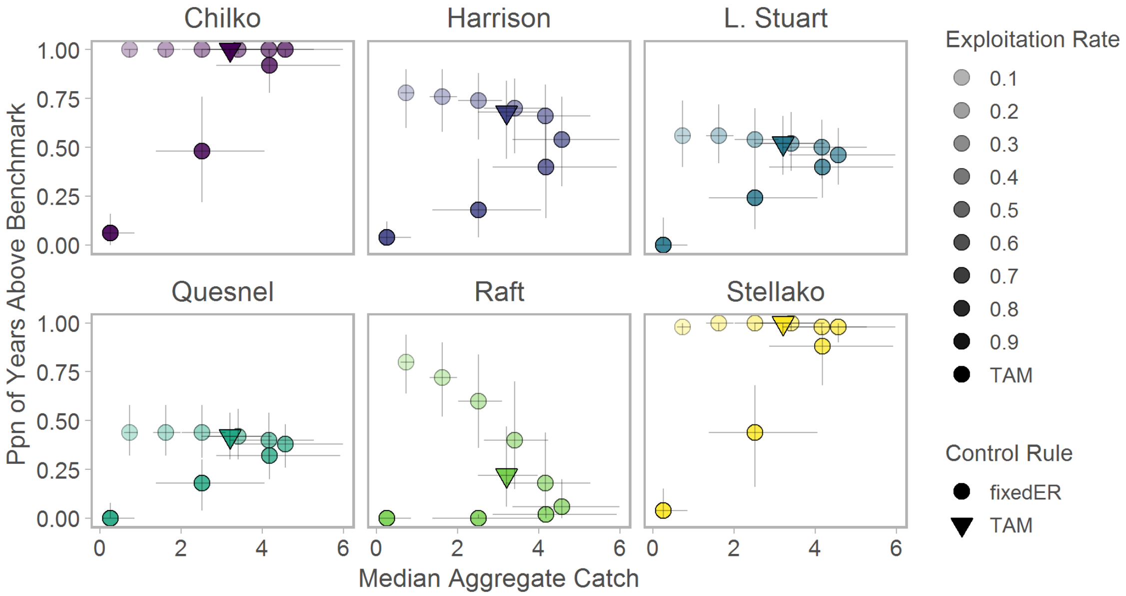

Figure 5. Trade-offs between aggregate catch (millions of fish) and the proportion of years above the lower biological benchmark for various fixed exploitation rates (circles) and the total allowable mortality (TAM) harvest control rule (triangle). Points represent median values and whiskers the 90th percentile interval across Monte Carlo trials. Output of function: plotCUTradeoff().

threats, beyond harvest. Identifying metrics such as these in a structured and repeatable way would be beneficial for COSEWIC Recovery Potential Assessments, SARA Recovery Strategies, and Bill C-68 Rebuilding Plans. The modelling tool that has been developed for this project could be adapted to calculate these types of metrics.

- The model could include a greater selection of generic harvest strategies to capture the basic management types for Pacific salmon. For example, fixed escapement goal and abundance-based escapement goals could augment currently available HCRs (fixed exploitation rate and abundance-base exploitation rate). In addition, a customizable HCR generating function could be included.
- The model's forecast component could be directly incorporated into HCRs to represent data-rich MUs where forecasts or in-season assessments are required to apply abundance based HCRs.
- The model could include changes in capacity over time within the spawner-recruitment relationship to represent deteriorating habitat conditions or habitat mitigation efforts. Information on changes in capacity could be derived from RAMS, Risk Assessment Methodology for Salmon, output (Hyatt et al. 2017; DFO 2018). In addition, both enhancement and habitat mitigation levers could be added to the management procedure to more fully capture rebuilding options.
- The model could be adapted to directly incorporate environmental covariates (e.g., abundance of competitors, sea surface temperature) in the stock-recruit relationship. Previously published estimates of the strengths of these effects (Connors et al. 2020)

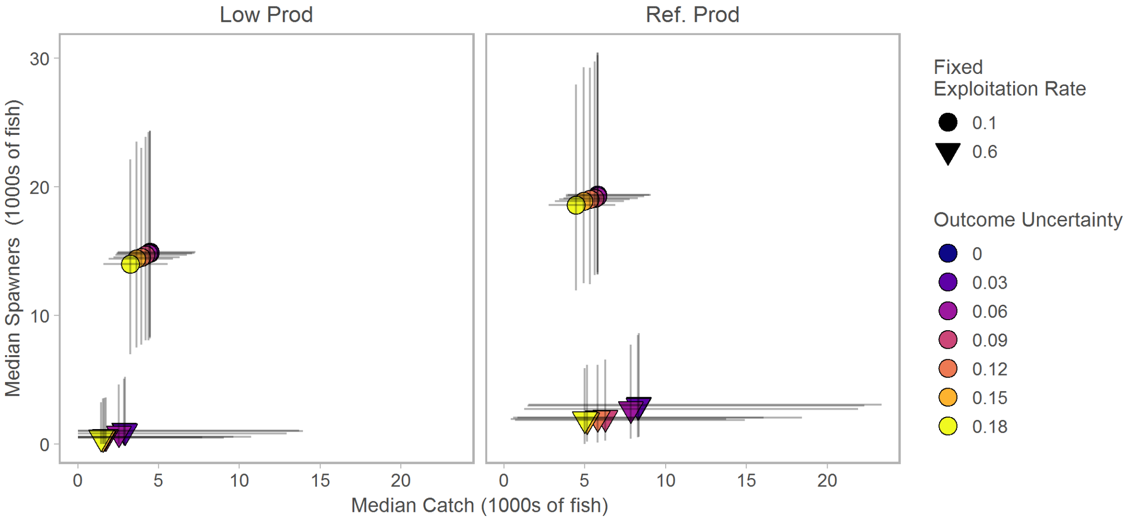

Figure 6. Trade-offs between median aggregate catch (1000s of fish) and the median aggregate spawner abundances (1000s fish) for outcome uncertainties from 0-0.18 standard deviations (colours) and for fixed exploitation rate equal to 0.1 (circles) and 0.6 (triangles). Left and right panels represent low and average productivity, respectively. Points represent median values and whiskers are 90th percentile acros Monte Carlo trials.

would be used to realistically parameterize the operating model. Analysts could then determine to what extent recovery may be constrained by basin-scale environmental processes.

- The model could consider variable weights for CUs within performance measures. For example, if one CU has high recovery potential or is prioritized by a large number of stakeholders, decision-makers may wish to weight it higher than others when looking at aggregate performance.

- For mixed-stock fisheries, CU-specific harvest control rules could be included in future iterations including, for example, Excess Salmon to Spawning Requirements, ESSR, and Food Social and Ceremonital, FSC fisheries; however, these would require detailed input from Fisheries Management and need to be developed on a case-by-case basis.

- There is a potential to apply this tool to more complicated multi-species fisheries in which MPs are evaluated against objectives for both target and non-target species. This type of functionality will be important for stocks like natural-origin Coho salmon in which impacts come primarily from incidental catch from fisheries on other species. While a case study such as this has not yet been examined, fisheries within the model could be structured to represent non-target fisheries and, potentially, multiple species, though these changes would dramatically increase the complexity of the model due to differences in age structure.

- It may be possible to evaluate the impacts of changes in assessment frequency and intensity using proxies in the simulation model by changing the variances in observation errors in the assessment sub-model and adding possible biases. Also, it may be possible to approximate those variances retrospectively with historical data. This module could answer important questions about the potential benefits of additional assessment or implications of the further loss of assessment programs.

- There may be value in combining this tool with RAMS and Priority Threat Management, PTM at different spatial scales. For example, information on changes in capacity from watershed-level RAMS could be included in CU-specific parameterizations of stock-recruitment relationships in this tool. Threats identified from PTM could be included in this model, and this model could identify where harvest is not a primary threat and others should be identified within PTM.

3.1 Recommendations for developing decision-support tools for Pacific salmon

The `samSim` model described in this report represents one of many available decision-support tools that can be used to inform fisheries management. `samSim` focuses on a detailed quantitative analysis of a narrow aspect of recovery planning (harvest decision-making), while other tools exist that take a more comprehensive but qualitative approach to evaluating recovery options. Although we have made initial suggestions about how `samSim` could be used in conjunction with some of these other tools, we recommend that a review of various decision-support tools for the management of Pacific salmon be included in a strategic plan or a guidance document for Pacific salmon, providing advice on the conditions under which each tool is most useful including costs and resource requirements. Lessons learnt from application of various tools could be compiled in a report to inform this review. For examples, keys to success of RAMS have been identified from case studies, e.g., on Barkley Sound where the use of a skilled facilitator to elicit expert opinion on key parameters was beneficial. In addition, Kronlund et al. (2016) identified necessary conditions for MSE when informing fisheries management within DFO. Limitations to the application of MSEs are also described in Kronlund and Marentette (2019). A first step is for DFO Science to develop a table of potential decision-support tools for consideration.

A gap highlighted by project participants was the failure to rigorously include socioeconomic and cultural objectives when identifying trade-offs among management procedures. The inclusion of social scientists and social-cultural knowledge holders may be necessary to elicit those objectives, thereby contributing to the success of the process by better capturing the underlying values of partners. When these objectives cannot be included directly within simulation models, this expertise may still be required to integrate socio-economic and cultural objectives into the broader evaluation of management strategies.

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5 Appendices

5.1 Example Objectives/Performance Metrics from Other Jurisdictions

Example 1 – Viability and Risk Assessment Procedure (VRAP) for Puget Sound Chinook salmon (NOAA Fisheries Service 2017)

VRAP is a process implemented by the National Marine Fisheries Service, NMFS, to calculate exploitation rates for Pacific Salmon in the US based on upper and lower benchmarks (Rebuilding Escapement Threshold (RET) and Critical Escapement Threshold (CET), respectively). For each population, a RET is defined as spawner abundance at MSY (if stock-recruitment data are available), or an absolute abundance derived from the conservation literature in the absence of data, e.g., 1250 spawners for Puget Sound Chinook Salmon (NOAA Fisheries Service 2017). A CET is defined as 5% of equilibrium spawner abundance, or an absolute abundance derived from the conservation literature, e.g., 200 spawners for Puget Sound Chinook Salmon. The rebuilding exploitation rate is set by evaluating performance over a range of exploitation rates and selecting the largest exploitation rate where less than 5% of simulation runs are below CET over 25 years, and the smallest exploitation rate where greater than 80% of runs are above RET over 25 years.

Example 2 – US rebuilding plans for federally regulated fisheries under the Magnuson-Stevens Act (National Research Council 2014)

For federally regulated fisheries in the US (including Pacific Salmon) the Magnuson-Stevens Acts legally mandates the implementation of rebuilding plans for overfished stocks. NFMS guidelines for rebuilding describe the requirements based on:

- A target stock size
- A minimum stock size, below which rebuilding plans are required (e.g., for Pacific salmon, spawning biomass < 0.5 or 0.75 MSY levels; National Research Council (2014))
- A minimum acceptable probability of rebuilding to the target, set by management
- Target time for recovery bounded by minimum and maximum limits, where the minimum time (Tmin) is estimated using simulated stock projections in the absence of fishing and the maximum time is a function of both Tmin and the generation time of the species

Rebuilding analyses are comprised of projections in a closed-loop simulation model for a range of fishing mortality rates to identify those that achieve rebuilding targets with an acceptable probability within the maximum time frame. A set of decision rules are implemented if stocks fail to rebuild in order to revise targets and fishing mortality rates within the rebuilding plan (Wetzel et al. 2016).

Example 3- The Committee on the Status of Endangered Wildlife in Canada, COSEWIC

COSEWIC has identified critical thresholds on abundances to delineate conservation risks for Endangered and Threatened populations at 250 and 1000 mature individuals, or 2500 and

10,000 mature individuals when combined with declining trajectories, respectively. COSEWIC further identified thresholds on probabilities of extirpation for Endangered and Threatened categories, at 10% over 100 years and 20% over 5 generations or 20 years, whichever is longer. These thresholds are analogous to those used by IUCN and are derived from conservation literature on population dynamics at small population sizes across terrestrial and aquatic species.

See Appendix Table 1 for example performance metrics linked to management objectives commonly considered for Pacific salmon. See Appendix Tables 2, 3 and 4 for lower rebuilding thresholds, extirpation thresholds, and upper rebuilding thresholds used in other case studies.

Table 1. Examples of objectives and performance metric that could be used to rebuild Pacific salmon CUs

Overarching goal	Performance metrics
Rebuild depleted CUs (These performance metrics infer a relatively monotonic trajectory towards a rebuilding target)	Probability that any one (or a specified proportion of) red-status CU(s) rebuilds to above its lower rebuilding threshold within a given time frame.
	Probability that all red-status CUs rebuild to above their lower rebuilding thresholds (e.g., lower WSP benchmark) within a given time frame.
	Proportion of red-status CUs that rebuild to above their lower rebuilding thresholds with a specified probability within a given time frame. (Median over MC trials and 95% CIs)
	Number of years required to achieve lower rebuilding thresholds for one (a proportion of, or all) red-listed CU(s) with a specific probability. (Median over MC trials and 95% CIs)
Minimize risk of loss (These metrics can be duplicated for numerous rebuilding and target thresholds)	Proportion of years that all CUs are above a quasi-extirpation threshold across the modelled time period. (Median over MC trials and 95% CIs)
	Proportion of years where all CUs are above their lower rebuilding thresholds within the modelled time period. (Median over MC trials and 95% CIs)
	Proportion of years where at least one (or a specified % of) CU(s) is(are) above their lower rebuilding thresholds within the modelled time period. (Median over MC trials and 95% CIs)
	Proportion of years where all CUs remain above their lower (or upper) rebuilding threshold across the modelled time period. (Median over MC trials and 95% CIs)
	Mean spawner abundances over the modelled time-period (or most recent generation) relative to lower rebuilding threshold. (Median over MC trials and 95% CIs)
	Variation in spawner abundances: CV of (or average % change between years in) spawner abundances over the modelled time period. (Median value over MC trials and 95% CIs) (suggested as indicator of extinction risk by Wainwright and Waples 1998)
Avoid COSEWIC listing	Short-term trends in spawner biomass over the last three generations. (Median over MC trials and 95% CIs) *COSEWIC Criterion A*
	Probability that short-term trends in abundances are > 30% (COSEWIC threshold) in the most recent time period. *COSEWIC Criterion A*
	Proportion of years where the short-term trend metrics < 30% for all CUs (or specified % of CUs). (Median over MC trials and 95% CIs) *COSEWIC Criterion A*

Overarching goal	Performance metrics
	Proportion of years where the short-term trend is stationary or positive and abundances are greater than 10,000. *COSEWIC Criterion C*
	Proportion of years where all CUs are above COSEWIC small population size thresholds, across the entire sampling period. (Median over MC trials and 95% CIs). *COSEWIC Criterion D*
Maintain exploitation rates below sustainable levels	Mean exploitation rate relative to current U_{MSY} for over the modelled time period. (Median value over MC trials and 95% CIs)
Maximize catch and stability in catch	Proportion of years that mean catch for the CU-aggregate is above a minimum acceptable level over the entire sampling period, in the short term (first 1-2 generations), or in the long term (last 1-2 generations). (Median value over MC trials and 95% CIs)
	Mean catch over the entire sampling period, in the short term (first 1-2 generations), or in the long term (last 1-2 generations), for totals and segregated into different fisheries (e.g., mixed-CU vs. terminal). (Median value over MC trials and 95% CIs)
	Catch variability: CV of (or average % change between years in) catch over the sampling period, for totals and segregated into different fisheries (e.g., mixed vs. terminal). (Median value over MC trials and 95% CIs)
Allocate catch to terminal vs. mixed-CU fisheries	-Proportion of catch in mixed-CU vs terminal fisheries averaged over the entire sampling period (Median value over MC trials and 95% CIs)

Table 2. Candidate lower rebuilding thresholds and examples from case studies

Category	**Description**	**Threshold (Reference)**
Wild Salmon Policy lower benchmark*	Level which provides a substantial buffer between it and levels that would lead to CU being considered at risk of extirpation by *COSEWIC*	*Sgen*, spawner abundances that will recover to *SMSY* within 1 generation in the absence of fishing under equilibrium conditions (1)
		25th percentile of observed spawner abundances (2)
		20% of spawners at maximum recruitment, *Smax* (1,3,4)
COSEWIC thresholds*	Endangered (Criterion D)	250 (5)
	Threatened (Criterion D)	1000 (5)
	Endangered, when combined with continuing decline (Criterion C)	2500 (5)
	Threatened, when combined with continuing decline (Criterion C)	10,000 (5)
Pacific Fisheries Management Council, US	Definition of “overfished” for Pacific salmon, below which rebuilding plans must be developed	0.5*BMSY* or 0.75*BMSY* (6)
NMFS, Viability and Risk Assessment Procedure (VRAP) for computing Rebuilding Exploitation Rates (RERs)	Critical escapement threshold (CET), represents a boundary below which uncertainties about population dynamics increase substantially related to genetic and environmental risks	5% equilibrium spawner abundances, or 42-417 annual spawners (7)
		200 annual spawners (for Puget Sound Chinook Salmon) (7,8)
Cultus Lake Sockeye Salmon Recovery Objectives	Ensure the genetic integrity of the population	1000 successful adult spawners, averaged over a generation, with no fewer than 500 in any one year (9)
Sakinaw Lake Sockeye Recovery Objective	Safeguard genetic diversity with interim milestones	500 natural adult spawners after 2 generations and 1000 after 4 generations (10)
Interior Fraser Coho Salmon Recovery Objectives	Secure the long term viability and diversity of naturally spawners	1000 natural spawners in at least half of sub-populations, averaged over 3 years (11)

*WSP and COSEWIC assess number of mature individuals as the geometric mean spawner abundance over the most recent generation to compare against thresholds. In contrast, other assessments have compared similar thresholds against total population size calculated as the product of the mean spawner abundances × the average generation length (Allendorf et al. 1997) to assess risks of extinction related to genetic effects. NOAA (2017) reported in fish/year.

(1) (Holt et al. 2009)
(2) (Holt et al. 2018)
(3) (Johnston et al. 2002)
(4) (Shortreed et al. 2001)
(5) (COSEWIC 2015)
(6) (National Research Council 2014)
(7) (McElhany et al. 2000)
(8) (NOAA Fisheries Service 2017)
(9) (Cultus Sockeye Recovery Team 2009)
(10) (Sakinaw Sockeye Recovery Team 2005)

Table 3. Candidate extirpation thresholds and examples from case studies

Category	**Description**	**Threshold (Reference)**
From the conservation literature	Quasi-extirpation threshold for salmon	100 fish (50-250) for four consecutive years (1,2)
NMFS, Viability and Risk Assessment Procedure (VRAP) for computing Rebuilding Exploitation Rates (RERs)	Quasi-extirpation threshold for salmon	250 fish/generation (3)
COSEWIC definitions for categories for extirpation	Threatened	10% chance of extirpation over 100 years (4)
	Endangered	20% chance of extirpation within the longer of 5 generations or 20 years

(1) (Holt and Bradford 2011)
(2) (Allendorf et al. 1997)
(3) (Sands 2012)
(4) (COSEWIC 2015)

Table 4. Candidate upper rebuilding threshold and examples from case studies

Category	Description	Threshold (Reference)
Wild Salmon Policy upper benchmark	Level expected to provide maximum catch on an average annual basis, given existing environmental conditions	80% *SMSY* or *SMSY* (1)
		50th percentile of observed spawner abundances (2)
		40% of spawners at maximum recruitment (*SMAX*) (1)
NMFS, Viability and Risk Assessment Procedure (VRAP) for computing Rebuilding Exploitation Rates (RERs)	Rebuilding Escapement threshold (RET), where rebuilding plans are no longer required based on low risk of extirpation	SMSY or 250-2500 (3)
		1250 (for Puget Sound Chinook Salmon) (3,4)
NMFA, Lower Columbia River Tule Chinook	Upper escapement threshold	The larger of either the estimated spawning abundance that would produce modeled MSY, or the average natural origin spawning abundance over the time series analyzed (5)
Cultus Lake Sockeye Salmon Recovery Objectives	A level of abundance that will support ecosystem function and sustainable use over the long term	*SMSY* (or a %); a proportion of the productive capacity of the lake; historic abundance; the abundance at which ecosystem function is maintained (6)
Sakinaw Lake Sockeye Recovery Objective	The level of abundance required to support ecosystem function and sustainable use over the long term	*SMSY*; the average number of spawners observed historically before the run collapsed; the number of spawners required to seed the lake above some minimum proportion of its productive capacity (7)
Interior Fraser Coho Recovery Objective	Long-term recovery goal so that societal objectives can be achieved	1000 naturally spawning in all sub-populations (8)

(1) (Holt et al. 2009)
(2) (Holt et al. 2018)
(3) (McElhany et al. 2000)
(4) (NOAA Fisheries Service 2017)
(5) (Ford et al. 2007)
(6) (Cultus Sockeye Recovery Team 2009)
(7) (Sakinaw Sockeye Recovery Team 2005)
(8) (Interior Fraser Coho Recovery Team 2006)

5.2 Modules proposed for inclusion in simulation evaluation

5.2.1 Climate-driven changes in productivity of CUs

Pacific salmon CUs often exhibit temporal variability in productivity (Peterman and Dorner 2012) that appears to be associated with ocean basin- and/or regional-scale changes in environmental conditions (Mantua et al. 1997; Mueter et al. 2002). Changes in environmental or biological drivers (e.g. sea surface temperature, SST, competition) may moderate productivity via altered marine survival rates (Mueter et al. 2002) and may change patterns of coherence among CUs, resulting in increased synchrony (Kilduff et al. 2015). Under anticipated climate change scenarios, the influence of large-scale environmental drivers on CU dynamics may limit efforts to rebuild CUs from depleted states. Is rebuilding even feasible under climate-driven reductions in productivity? Climate-driven variability in productivity will be simulated in the operating model by including short and long-term patterns in productivity (e.g., random variations with autocorrelation, or regime-like step functions (Dorner et al. 2009) or persistent trends in productivity over time (Dorner et al. 2013). Further scenarios of changes in covariation in recruitment dynamics among CUs under climate change will be considered. Climate projections for coastal SST (IPCC 2014) can be used to force temporal trends in productivity in the model given observed correlations between SST and productivity (as in Dorner et al. (2013)).

Example Management Questions:

- Which MPs are associated with an acceptable high probability of rebuilding under low (similar to lowest observed) or variable productivity (e.g., similar to PDO-like cycles)?
- How does MP performance change under various IPCC scenarios of climate change?
- How does uncertainty in MP performance change when productivity trends are assumed to be cyclic (i.e., associated with regimes) vs. linear (i.e., associated with linear increase in SST)?
- How does synchrony (or asynchrony) in recruitment deviations among conservation units affect rebuilding performance among candidate MPs?

5.2.2 Mixed-CU fisheries

Pacific salmon are often harvested in mixed-CU fisheries that contain both abundant and depleted CUs. Simulation tools can be used to quantify trade-offs between achieving rebuilding targets and maintaining access to fisheries, while aiding in the documentation of those decisions. Simulation tools can also be used to evaluate related questions, such as the extent to which shifting effort from mixed-CU to terminal fisheries might maintain catch levels while reducing incidental take of non-target CUs. We intend to design MPs that include terminal and mixed-stock fisheries. Variable harvest rates among CUs in mixed-stock fisheries will be incorporated into the model via a combination of shared and CU-specific exploitation rates, with varying levels of associated uncertainty.

Example Management Questions:

- How large are the impacts of mixed-CU fisheries on low abundance CU's rebuilding probabilities or time frames relative to other sources of variability in productivity (i.e. natural mortality)?
- Which MPs preserve low abundance CUs while still maintaining mixed-CU fisheries?
- By how much would rebuilding time frames and/or probabilities of rebuilding be improved by a greater emphasis on terminal fisheries relative to mixed-CU fisheries?
- How does varying exploitation rates in mixed-CU fisheries influence the availability of spawners to terminal fisheries?
- How is ability to achieve rebuilding targets impacted from shifts to terminal fisheries (e.g., First Nations and recreational), which tend to be associated with greater outcome uncertainties?

5.2.3 Age-structured exploitation rates

Fisheries on Chinook Salmon are unique among Pacific salmon species in their exploitation of immature life stages. Age-specific exploitation rates can be incorporated into the model to better capture dynamics for Chinook Salmon.

Example Management Questions:

- What is the relative performance of MPs on rebuilding and harvest objectives for Chinook Salmon?
- To what extent will the probability of rebuilding improve if fishing mortality on earlier age classes/smaller sizes is reduced?

5.2.4 Observation error and survey effort

Fisheries managers are required to adopt a precautionary approach when setting exploitation rates and, as a result, greater uncertainty in CU status is typically associated with reduced exploitation rates. By developing MPs that incorporate different levels of uncertainty in abundance estimates, we can explore how greater survey effort (e.g., catch monitoring and spawning ground escapement assessment programs) can lead to higher exploitation rates while maintaining the same probability of meeting rebuilding targets (or reduced survey effort will require reduced exploitation rates to meet rebuilding targets at the same probability).

Example Management Questions:

- How does the performance of management procedures relative to one another change as survey effort and/or frequency and data quality improve?
- What is the difference in average catch between a data-rich and a data-limited CU assuming similar dynamics and rebuilding goals (e.g., value of improved surveys)?
- What component of the assessment (spawning escapement, CU-specific catch, age-at-maturity) has the greatest influence on rebuilding performance?

5.2.5 Changes in habitat capacity

Like productivity, the carrying capacity of a given CU may change through time due to the restoration or deterioration of freshwater habitat, or change in freshwater survival. Although these changes likely reflect different management actions outside the scope of this project, they could be incorporated in our model by making relatively coarse adjustments to the spawner-recruitment relationship in the operating model. This module could be extended from module 1 above.

Example Management Questions:

- Given observed declines and projected future declines in freshwater habitat capacity, what are implications for achieving rebuilding and harvest objectives?
- What is the relative impact of improvements to habitat capacity compared with reductions in exploitation on the ability to achieve rebuilding and harvest objectives? Is recovery more/less sensitive to changes in habitat capacity or exploitation?

5.2.6 Depensation

Evidence suggests that certain salmon CUs may exhibit depensation at low spawner abundances, i.e. low levels of per capita productivity despite negligible competition. These effects may be due to reduced success at finding mates, greater per capita mortality due to predation, or reduced genetic diversity and fitness. Various forms of depensation could be addressed by incorporating different CU recruit relationships across operating models.

Example Management Questions:

- What is the maximum exploitation rate that would have an acceptable low probability of quasi-extinction given depensation (though not necessarily achieving rebuilding objectives)?
- For severely depleted CUs, what are the impacts of various hypotheses on depensation on rebuilding potential? Can we expect recovery without additional management measures (e.g., enhancement)?