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# Guidelines for Defining Limit Reference Points for Pacific Salmon Stock Management Units

Carrie. A. Holt[1], Kendra Holt[2], Luke Warkentin[1], Catarina Wor[1], Brendan Connors[2], Sue Grant[3], Ann-Marie Huang[3], Julie Marentette[4]

[1]Fisheries and Oceans Canada, Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

[2]Fisheries and Oceans Canada, Institute of Ocean Sciences
9860 W Saanich Road
Sidney, BC V8L 5T5

[3]Fisheries and Oceans Canada, Annacis Office
100 Annacis Pkwy Unit 3
Delta, BC V3M 6A2

[4]Fisheries and Oceans Canada, National Headquarters
Ottawa, ON, Canada

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**Foreword**

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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## ABSTRACT

Limit reference points, LRPs, define the stock status below which serious harm is expected to occur to a stock. LRPs are required for major fish stocks, or Stock Management Units (SMUs) that are prescribed by regulation under amendments to the Canadian *Fisheries Act* (2019). Pacific salmon are unique among marine fish stocks due to their high levels of intraspecific diversity which gives rise to a large range in data availability, considerations, and approaches for assessments and LRP development. In this paper, we identify six principles for developing LRPs for Pacific salmon that are adapted from principles used more broadly among marine species. One principle unique to Pacific salmon is that LRPs should be aligned with Canada's Wild Salmon Policy (WSP) objective of preserving biodiversity of salmon at the scale of Conservation Units (CUs), which are nested within SMUs. We developed methods for calculating LRPs, and established guidelines on how to implement them including under which conditions they should or should not be applied. We propose that LRPs be identified from the proportion of CUs that have status above the Red zone for WSP status assessments, as a default approach. This provides some consistency with status assessments already produced under the WSP, and can inform management decisions for harvest, habitat and hatcheries that often occur at finer, CU scales. To supplement the default approach, we provide LRPs based on metrics of aggregate abundances for the entire SMU, which may be required for fisheries management purposes in some cases. These latter LRPs are derived to have a desired probability of all component CUs being above Red status given an assumed relationship between aggregate abundance and the probability that all CUs will be above Red status. We identify uncertainties associated with each approach, and describe how they can be applied across a range of data types, qualities and quantities. Analyses to support our development of guidelines has been informed by three cases studies: Interior Fraser Coho Salmon *Oncorhynchus kisutch*, West Coast Vancouver Island Chinook Salmon, *O. tshawytscha*, and Inside South Coast Chum Salmon, *O. keta*, excluding the Fraser River.

# 1. INTRODUCTION

## 1.1. BACKGROUND

**KEY POINTS:**

- The revised *Fisheries Act* includes new Fish Stocks provisions that introduced legal obligations to identify limit reference points (LRPs) for major fish stocks prescribed under regulation.
- Under DFO's Precautionary Approach Framework, LRPs define the stock status below which serious harm is expected to occur to the stock.
- Canada's Wild Salmon Policy (WSP) includes an objective to safeguard the genetic diversity of wild Pacific salmon by maintaining and protecting Conservation Units (CUs), the focus of biological assessments under the WSP.
- The revised *Fisheries Act* indicates that a single LRP is required for each major fish stock, defined as Stock Management Units (SMUs) for Pacific salmon, which are groups of CUs managed as a unit to achieve joint status.
- This provision created the need for the development of methodologies to estimate LRPs for assessment and management at the SMU level, while considering the need to maintain CUs within an SMU above their lower benchmarks under the WSP.

Amendments to the Canadian *Fisheries Act* (2019) include new Fish Stocks provisions that introduce legal obligations to manage stocks to promote sustainability and avoid biological limit reference points, LRPs (DFO 2021a). The provisions also require plans to rebuild fish stocks that have declined to, or below, an LRP while taking into account the biology of the fish and environmental conditions experienced by the stock. These obligations apply to major fish stocks that are prescribed under regulations. They reinforce the previously established DFO policies to manage stocks consistent with the precautionary approach. These include The Fishery Decision Making Framework Incorporating the Precautionary Approach (DFO 2009a), also known as DFO's Precautionary Approach Framework within the Sustainable Fisheries Framework and Canada's Wild Salmon Policy (DFO 2005).

Under DFO's Precautionary Approach Framework, LRPs represent the stock status below which serious harm is expected to occur to the stock. Definitions of serious harm within the DFO literature tend to focus on impaired productivity, although other aspects of serious harm are sometimes captured (see grey box below, adapted from Marentette et al. (In prep.)[1]).

[1]Marentette, J.R., Barrett, T., Cogliati, K.M., Ings, D., Ladell, J., Thiess, M. Operationalizing Serious Harm: Existing Guidance and Contemporary Canadian Practices. Can. Sci Avis. Secr. Res. Doc. In prep.

### 1.1.1. Interpretations of serious harm

Serious harm has been interpreted as any changes to the biological properties of the stock that make growth or rebuilding to target levels cease to be considered rapid and secure[1]. These changes are considered difficult to reverse[2,3], and can be associated with:

- impaired productivity[1-6] resulting from changes to biological processes such as recruitment, growth, maturation and survival[1,4];
- a loss of resilience[5] (an impaired ability to rebuild or to recover from perturbation[6]);
- increased risk of depensation or Allee effects[4]; and/or
- more generally, states where population dynamics cease to be well-understood[4].

At this status level, there may also be resultant impacts to the ecosystem, associated species and a long-term loss of fishing opportunities[6]. Serious harm may be due to fishing, other human-induced mortality, or changes in population dynamics unrelated to fishing[4].

[1](DFO 2016a); [2](Kronlund et al. 2018); [3](Shelton and Rice 2002); [4](DFO 2006); [5](Smith et al. 2012); [6](DFO 2009a)

The definition of serious harm from DFO (2009a) indicates that LRPs should be *above* the level where serious harm is expected to occur, not at the level where it is occurring, and that long-term losses of fishing opportunities may occur below that level. Defining the level before serious harm occurs to a species or ecosystem is a pervasive challenge as harm is often not identified until it is already occurring (Hilborn and Walters 1992) and population dynamics are not well understood at low population sizes (DFO 2006; Keith and Hutchings 2012). Also, this definition of serious harm includes possible impacts on other ecosystem components, which are often challenging to identify because of limited data and poor understanding of ecosystem linkages and dynamics (but see Chagaris et al. 2020).

Pacific salmon are unique among marine fish species due to their high levels of intraspecific diversity which gives rise to a large range in data availability, considerations, and approaches for assessments and LRP development. These differences necessitate guidance on LRP methods that is specific to Pacific salmon, while being consistent with the principles for LRP development across species (Marentette et al. In prep.).

Canada's Wild Salmon Policy, WSP, represents DFO's implementation of the Precautionary Approach Framework for Pacific salmon. The goal of the WSP is to restore and maintain healthy and diverse salmon populations and their habitats for the benefit and enjoyment of the people of Canada in perpetuity (DFO 2005). One objective of the WSP is to safeguard the genetic diversity of wild Pacific salmon by maintaining and protecting Conservation Units (CUs), where a CU is defined as a "group of wild salmon sufficiently isolated from other groups that, if extirpated is very unlikely to recolonize naturally within an acceptable time frame, such as a human lifetime or a specified number of salmon generations" (DFO 2005).

Genetic and phenotypic diversity among CUs is important because it allows for diversity in responses to threats and environmental drivers, contributing to the sustainability of the species and the ecosystem services they provide (Price et al. 2021). Portfolio effects have been shown to dampen interannual variance in aggregate-level abundances due to independent dynamics among component populations or CUs (Schindler et al. 2010). Population and life-history diversity may buffer species from environmental variability and contribute to long-term stability through differing responses to environmental changes. However, deterioration of portfolio effects have been observed for Pacific salmon in Canada due to synchronous declining trends in abundances related to changes in climate and marine and freshwater habitats, as well as fishing practices that have historically overfished weak populations (Price et al. 2021).

Under the WSP, the status of individual CUs is inferred by comparing status indicators to biological benchmarks delineating three zones: Green, Amber, and Red. These zones represent increasing conservation concern from Green to Red requiring increasing management intervention. The lower benchmark, delineating the Red and Amber zones, is intended to be at the level to "ensure there is a substantial buffer between it and any level of abundance that could lead to a CU being considered at risk of extinction by COSEWIC", where COSEWIC is the Committee on the Status of Endangered Wildlife in Canada (DFO 2005; Holt et al. 2009). In practice, CUs in the WSP Red zone tend to align with Endangered or Threatened COSEWIC statuses, and Green with Not at Risk COSEWIC categories.

#### 1.1.2. Spatial scales of assessment

Salmon have a complex hierarchical populations structure that extends from taxonomic species to local demes or spawning locations (Fig. 1). CUs are nested within taxonomic species and major life-history variants, such as ocean- and stream-type for Chinook Salmon, *Oncorhynchus tshawytscha*, and populations are nested within CUs (DFO 2005). While assessments of Pacific salmon under the WSP has focused on setting benchmarks for individual salmon CUs (DFO 2005), the revised *Fisheries Act* indicates that a single LRP is required for each major fish stock(DFO 2021a). In the context of Pacific salmon, major fish stocks are defined as Stock Management Units (SMUs), which are groups of CUs that are managed as a unit to achieve joint status (DFO 2021b). The delineation of SMUs was in part a response to the national-level requirement for delineating major stocks for Pacific salmon under the *Fisheries Act*. This provision created the need for the development of methodologies to estimate LRPs for the assessment and management of fisheries at the SMU level, while considering the need to maintain all CUs within an SMU in Amber or Green zones, i.e., above Red status.

In addition to intrinsic biological reasons for assessing status at the CU scale, this scale is also relevant to various uses and management activities for Pacific salmon, e.g., local or terminal fisheries; food, social and ceremonial fisheries; hatchery enhancement; and watershed restoration and planning (Fig. 1). While the Fish Stocks provisions pertain to fisheries at scales relevant to marine harvest management, for many SMUs those fisheries have been restricted in recent decades (Grant et al. 2020b), such that habitat and hatchery management are playing an increasingly dominant role in management responses. Food, social and ceremonial use of salmon by First Nations occur at a variety of scales, often within CUs at the level of populations or specific spawning locations. In addition, threats and management responses extend to larger regional or aggregate-SMU scales, and across species, e.g., impacts related to climate change. Therefore, stock assessment and management are required at a hierarchy of spatial scales from within CUs to regional scales, across species.

Given the existing framework for assessing status of Pacific salmon by CU (Holt et al. 2009) and the similar intent between LRPs defined by DFO's Precautionary Approach Framework and lower benchmarks under the WSP, status against lower benchmarks can be used as a proxy for status against LRPs but applied at the scale of CUs instead of SMUs. The present work expands on assessment methods developed under the WSP by integrating statuses across CUs within an SMU and providing guidance on establishing LRPs at the scale of Pacific salmon SMUs. While CUs are nested within SMUs, the number of CUs within each SMU varies among salmon species. For example, SMUs for Sockeye Salmon, *Oncorhynchus nerka*, tend to contain a larger number of CUs than those for other salmon species because of the relatively high levels of local adaptation and biodiversity among spawning populations, and the associated small spatial scale of Sockeye CUs compared with other species.

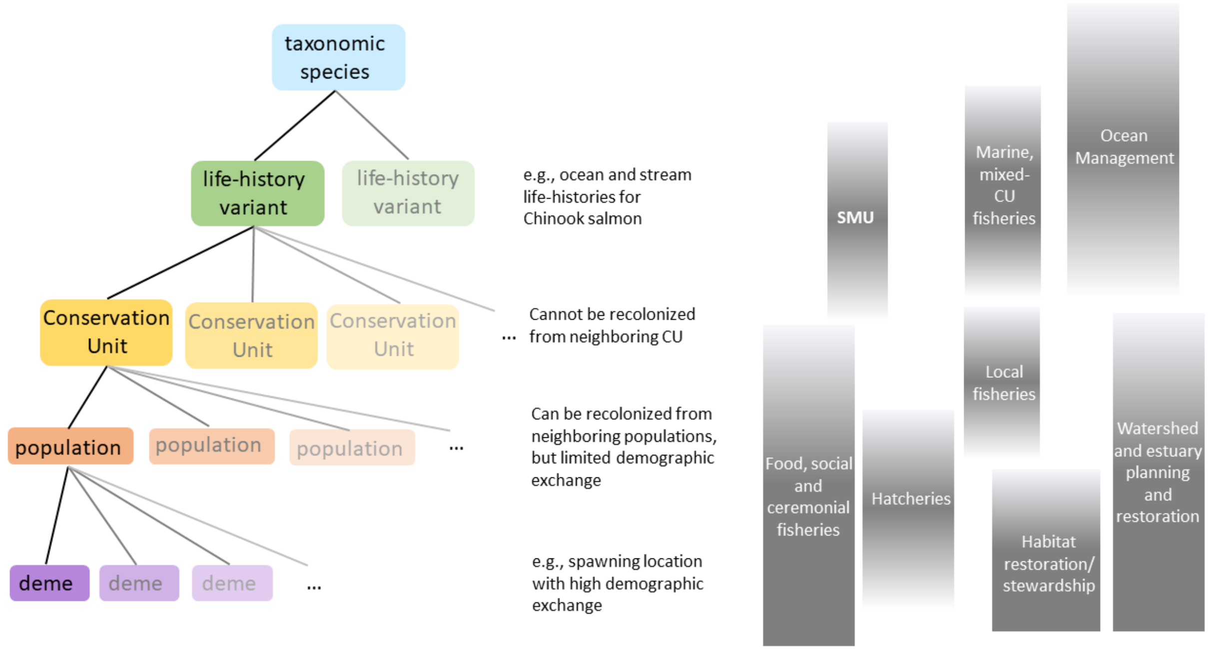


*Figure 1. Schematic representation of hierarchical, nested population structure of Pacific salmon (left) with the spatial scales of selected uses and management activities aligned with those scales, including the scale of Stock Management Unit, SMU (right).*

The existing framework for CU assessments includes consideration of the fine-scale distribution of spawners within CUs, e.g., at the stream level (DFO 2016b). Here we also consider the distribution of populations within CUs in the assessment when it is considered to be important for the sustainability of the CU or SMU. Identifying relevant spatial scales within CUs when assessing status can be challenging due to uncertainty and temporal variability in meta-population dynamics and the impacts of those dynamics on long-term viability, which represents a key source of uncertainty when defining LRPs.

Alternative spatial scales of assessment and management are used by agencies outside of DFO for Pacific salmon, including Designatable Units used by COSEWIC which largely align with DFO's CUs, and Stock Groups under the Pacific Salmon Treaty, which align to some extent with SMUs. These units are not considered further here. Although the LRPs presented are intended to be applied at the SMU scale, these methods could also be applied at smaller or larger scales to inform a variety of management decisions.

We highlight previous recommendations to develop Integrated Management Processes where management objectives (including those related to biodiversity and sustainability) and management actions are integrated across biological and socioeconomic relevant scales, sectors, and decision-making bodies (Withler et al. 2018). Importantly, Withler et al. (2018) recommend management systems that adaptively respond to statuses from routine assessments at relevant spatial scales.

## 1.2. GOALS, COMPONENTS, AND SCOPE OF THE RESEARCH DOCUMENT

**KEY POINTS:**

- The goals of this Research Document are summarized as:
    - Develop candidate methods for identifying LRPs for Pacific salmon that are consistent with the WSP objective of conserving biodiversity.
    - Document candidate methods for developing LRPs including data requirements and assumptions.
    - Document key uncertainties that affect LRP estimates.
    - Provide guidance and recommendations on the application of candidate methods over a range of data types and availability.
- The sections of this Research Document are as follows:
    - **Section 1.** Introduction: background and goals
    - **Section 2.** A review of reference points and their roles for Pacific salmon
    - **Section 3.** Principles for the development of LRPs for Pacific salmon
    - **Section 4.** Proposed LRP methods for Pacific salmon
    - **Section 5.** Guidelines on the implementation of LRPs including recommendations on when, and when not to use candidate LRP methods
    - **Section 6.** Recommendations on future research
- This paper is scoped to focus on the estimation of LRPs with corresponding guidelines, and does not include a full quantitative evaluation of those LRPs. That step is included as an important area of future research.

### 1.2.1. Goals

The goals of this Research Document as outlined in the Terms of Reference, were to:

- Develop candidate methods for identifying SMU-level LRPs for Pacific salmon that are consistent with the WSP objective of conserving biodiversity by maintaining CUs above lower biological benchmarks. These candidate methods include LRPs based on the status of component CUs and aggregate abundance over multiple CUs, where CU assessments can be developed using a multidimensional or single-metric approaches, as appropriate. (Section 4)
- Document candidate methods for developing LRPs at the SMU-level, including data requirements and assumptions. (Section 4 and Appendix B). More details are provided in Holt et al. (2023).
- Document key uncertainties that affect LRP estimates for each method considered, including uncertainties arising from missing or limited CU-level data. (Section 6)
- Provide guidance and recommendations on the application of candidate methods over a range of data types and availability. (Section 5)

### 1.2.2. What's in this Research Document?

This Research Document addresses these four goals, while the companion Research Document (Holt et al. 2023) provides a more detailed and technical descriptions of candidate methods for developing LRPs and more fully demonstrates their implementation on three case studies. Summaries of methods are included here for the completeness of these guidelines.

In particular, this paper has six sections:

1. Introduction
2. A review of reference points and their roles for Pacific salmon
3. Principles for the development of LRPs for Pacific salmon
4. A description of candidate LRP methods, with further details in Holt et al. (2023). Appendix A summarizes their application to three case studies.
5. Guidelines on the implementation of LRPs including recommendations on when, and when not to use each candidate LRP method
6. Discussion of uncertainties and recommendations on future research

This work was supported by a technical working group composed of DFO and First Nations analysts with analytical expertise in stock assessment and the biological basis of serious harm. The technical working group was not intended to be a venue for consultation or to capture stakeholder perspectives and socioeconomic objectives. While these considerations are relevant when developing management responses to stock assessments, they were not considered necessary for the development of analytical methods for LRPs.

#### 1.2.3. Scope

While candidate LRPs were evaluated to an extent through sensitivity analyses and retrospective analyses, a more rigorous closed-loop simulation evaluation of candidate LRPs was beyond the scope of both Research Documents, and is recommended as a next step. Also, our applications of LRP methods to case studies are for illustrative purposes only, and are not meant to be a formal estimation of LRPs for those SMUs. Additional LRP methods could be developed in the future, aligned with the key principles outlined here (Section 3).

Time-varying population processes, such as changes in productivity, have important impacts on biological benchmarks, LRPs, and assessment against LRPs. While we describe some recent approaches for considering those impacts in Section 6, a comprehensive review and evaluation of the impacts of time-varying parameters on LRPs is beyond the scope of this study. This theme is an important area for future research.

When developing LRPs, we follow the recommendations of Withler et al. (2018) to remove hatchery-influenced populations from biological assessments under the WSP when hatchery production predominates over natural production, as described in Section 4. Following recent WSP assessments, we also removed the demographic influence of hatchery production from time-series of abundances when data on the proportion of hatchery- vs. natural-origin fish on the spawning grounds were available in our case studies. An evaluation of methods for estimating proportion of hatchery-origin spawners or accounting for them in biological assessments was beyond the scope of this study.

Here we follow the recommendation of Holt et al. (2009) to assess status of CUs using multiple metrics, and have implemented this approach using the Pacific Salmon Status Scanner tool (or, Salmon Scanner), documented in Pestal et al. (In prep.)[2]. The Salmon Scanner was developed from the implementation of formal, peer-reviewed WSP assessments for Pacific salmon CUs in Canada (Section 4). A peer-review of the Salmon Scanner is planned for 2022 and is beyond the scope of this paper.

[2]Pestal, G., MacDonald, B, Grant, S, and Holt, C. Rapid Status Approximations from Integrated Expert Assessments Under Canada's Wild Salmon Policy. Can. Tech. Rep. Fish. Aquat. Sci. In prep.

Decisions about prioritizing CUs for management intervention within an SMU was also beyond our scope, and requires broader discussion with managers, First Nations, and stakeholders. This includes evaluating the costs and benefits of conserving individual CUs given differential vulnerability to climate change or other threats.

While one role of LRPs is to trigger the development of rebuilding plans under the Fish Stocks provisions, the content and implementation of rebuilding plans is beyond the scope of this paper. A full review of how LRPs can be integrated into salmon management processes outside of the Fish Stocks provisions (e.g., including management of habitat and hatcheries) is also beyond our scope, and is a gap that warrants further discussion. We highlight a few possible roles for LRPs in Section 2.2. Lastly, we do not review the current definition of 'major fish stock' as a SMU for Pacific salmon under the Fish Stocks provisions.

# 2. REVIEW OF REFERENCE POINTS AND THEIR ROLES FOR PACIFIC SALMON

## 2.1. INDICATORS AND REFERENCE POINTS FOR PACIFIC SALMON

**KEY POINTS:**

- LRPs have been widely adopted in Canadian fisheries.
- LRPs can be identified along a variety of indicators, and those indicators can be categorized as natural metrics, proxies for natural metrics, or composites of metrics.
- Under Canada's WSP, a composite of metrics ('multidimensional approach') is used in status assessments, including metrics on current spawner abundances, short and long-term trends in abundances, and the distribution of spawning, among others.
- DFO has recently developed the Pacific Salmon Status Scanner tool to rapidly approximate the multidimensional approach for salmon assessments.
- In some cases, single-metric approaches in which spawner abundances are compared with an abundance-based benchmark have been used as proxies for status under the WSP.

LRPs are common in the assessment and management of marine fisheries where they are used to identify and communicate status, as components of objectives, and to trigger changes in harvest rates among other roles (Kronlund et al. 2021; Marentette et al. 2021) (Section 2.2). LRPs have been widely adopted in Canadian fisheries. A review based on a survey of 177 Canadian stocks excluding salmonids and transboundary stocks, found that 58% had adopted LRPs, although the methods used to estimate LRPs varied considerably among stocks (Marentette et al. 2021).

LRPs and indicators of status can be categorized in ways that demonstrate the diversity of approaches that are available across data types and species life-histories. In particular, LRPs can be derived from theoretical relationships (e.g., stock-recruitment based reference points), historical patterns (e.g., abundance from which recovery has been observed in the past), or empirical analyses on abundances or life-history traits (Marentette et al. In prep.). For marine fish species, LRPs are typically estimated as a minimum level of spawning biomass (or proxy) that should not be breached (Shelton and Rice 2002; Kronlund et al. 2018; Marentette et al. 2021). DFO (2009a) identifies additional indicators such as catch rate indices, size and age profiles, and sex ratios that "can and should be considered for use in defining serious harm and guiding decision-making in relation to stock condition" (DFO 2009a). In general, indicators of status can be categorized as natural metrics (e.g., total abundances or other biological or population characteristics), a proxy for a natural metric (e.g., abundances of indicator stocks), or a composite of indicators that combine information over multiple dimensions or biological metrics of status (Marentette et al. In prep.).

The composite or multidimensional approach for assessing status, sometimes called a “traffic light” approach (Shelton and Rice 2002), is particularly useful when theoretical or historical abundance-based metrics are not estimable or applicable, or when data are limited (Dowling et al. 2015). Multidimensional approaches allow for consideration of numerous data sources often including expert knowledge to integrate conflicting metrics within assessments. For example, multidimensional reference points have been applied to Snow Crab, *Chionoecetes opilio*, in Canada, where data on catch per unit effort, egg clutches, and discards are integrated in stock assessments (Mullowney et al. 2018). Multidimensional approaches can also be useful to address mismatches in scales among biological stocks, the unit of management, and the spatial scale of data collection, when metrics capture processes at a variety of scales. These scale mismatches are not uncommon among marine species, especially invertebrate and salmonid species (DFO 2016a; Mullowney et al. 2020). They can create challenges when identifying LRPs at the scale of major stocks (DFO 2021a), and can make undesirable states in fish populations difficult to detect and mitigate.

Methods for estimating reference points for Pacific salmon are diverse, often taking advantage of its semelparous and anadromous life-history and limits on capacity in freshwater, and other population characteristics (Chaput et al. 2012; Portley and Geiger 2014). Under Canada’s WSP, status assessments integrate data across numerous indicators or metrics representing different population characteristics, including current spawner abundances, short and long-term trends in abundances, distribution of spawning, and fishing mortality relative to population productivity (Holt et al. 2009). Benchmarks are established for each metric and an overall multidimensional estimate of CU status is obtained by integrating status among metrics (Grant and Pestal 2013; DFO 2015; DFO 2016b; Grant et al. 2020a). An advantage of this approach is that CUs missing data for any single metric can still be evaluated against remaining metrics, making the framework applicable across a relatively broad range of data types and hence CUs. Expert-driven processes to integrate often conflicting metrics within the multidimensional framework have been implemented for numerous Pacific salmon CUs in Canada, such as Fraser River Sockeye Salmon (Grant et al. 2012, 2020a; Grant and Pestal 2013), Interior Fraser River Coho Salmon, *Oncorhynchus kisutch* (DFO 2015), and Southern BC Chinook Salmon (DFO 2016b). However, these expert-driven processes can be challenging to implement on a broad and timely basis due to the high demand they place on time and staff resources. Based on the consistencies that emerged from assessments where the integration of multiple metrics has been applied, Pestal et al. (In prep.) developed an algorithm to approximate overall WSP status by combining those metrics in a decision tree, at the scale of CUs. This algorithm was incorporated into DFO’s Pacific Salmon Status Scanner and then verified by local assessment experts and tested with ‘out-of-sample’ CUs not included in the original formulation (Pestal et al. In prep.).

In some cases, single-metric approaches in which spawner abundances are compared with an abundance-based benchmark have been used as proxies for WSP status both by organizations external to DFO (Commission 2016; Pacific Salmon Foundation 2020) and occasionally within DFO (e.g., Barkley Sockeye Salmon, Chaput et al. 2012). One recommended lower benchmark on spawning abundances under Canada’s WSP is $S_{gen}$, the abundance resulting in recovery to $S_{MSY}$ in one salmon generation under equilibrium conditions (Holt 2009). Benchmarks on spawner abundances for data-limited contexts have also been identified in recognition that the data required to estimate spawner-recruitment based benchmarks are often not available (e.g., Parken et al. 2006, Section 4.2). Biological benchmarks under the WSP are distinguished from triggers in harvest control rules that incorporate additional socioeconomic considerations beyond biological considerations (Holt and Irvine 2013).

## 2.2. ROLES OF LRPS IN CANADA

**KEY POINTS:**

- The roles of LRPs for marine fish stocks in Canada can include:
  - triggering rebuilding plans under the Fish Stocks provisions,
  - communicating conservation risks to decision makers and the public,
  - informing management decisions about fisheries as part of measurable objectives or operational control points, and
  - as a component of performance metrics within a Management Procedure Framework.
- Identifying LRPs is the responsibility of DFO's Science Sector.
- For Pacific salmon the application of LRPs has been limited, as fisheries management is often based on a wide range of management decisions made at different spatial scales (e.g., stream-level escapement goals, time-area closures, exploitation limits on aggregates).

For marine fish stocks in Canada, LRPs have several roles including triggering rebuilding plans under DFO's Precautionary Approach Framework (DFO 2009a) and the *Fisheries Act*, communicating conservation risks to decision makers and the public, and informing management decisions about fisheries. For example, LRPs can be used as part of measurable objectives and can also be applied as operational control points which are points where management actions are triggered within harvest control rules. A conservation goal might be to avoid low biomass levels where serious harm is expected to occur which can be translated to a measurable objective to avoid spawner abundances lower than an LRP with a high probability (e.g., 95%) over a specified time period. This objective can then inform the placement of operational control points within the harvest control rule. However, there can be several operational control points in the harvest control rule and these can be positioned to achieve a suite of biological and socioeconomic objectives beyond those associated with serious harm, usually by a diverse range of managers, First Nations, and stakeholders. In contrast, DFO's Science Sector is responsible for identifying LRPs based only on biological considerations (DFO 2021a).

In addition, LRPs can be used in performance metrics within a Management Procedure Framework (or Management Strategy Evaluation) to identify candidate procedures that achieve conservation objectives (e.g., 95% probability of staying above a LRP over a specified period) among other objectives (DFO 2021c). This approach explicitly accounts for a range of uncertainties in the biology of the stock, dynamics of the fleet, observations of abundances and ages at return, and the implementation of management decisions. Simulation evaluation of management procedures is widely viewed as a best practice for informing management decisions under uncertainty (Punt et al. 2020). For fisheries in which management procedures have been simulation tested, assessment of stock status relative to an LRP is not necessary so long as the management procedure selected has been demonstrated to meet conservation (and possibly other) objectives over a range of uncertainties (i.e., modelled scenarios) about stock and fishery dynamics. One advantage of this approach is that a single best underlying model (or LRP) describing the population and fleet dynamics need not be identified. Instead, management procedures can be evaluated against a suite of plausible underlying models or assumptions.

For Pacific salmon, the application of LRPs at the SMU-level has been more limited. Fisheries management for Pacific salmon is often based on a wide range of management decisions made at different spatial scales (e.g., stream-level escapement goals, time-area closures, exploitation limits on aggregates), instead of LRPs *per se*. Also, the application of Management Procedure Frameworks is not common for Pacific salmon where the impact of diverse management levers and their interactions are often difficult to quantify (e.g., hatcheries and harvest, though see the AHA model documented by HSRG (Hatchery Scientific Review Group) 2009). The roles of LRPs will likely evolve for Pacific salmon over time, and an exhaustive review is beyond the scope of this paper.

# 3. PRINCIPLES FOR LRP DEVELOPMENT

## 3.1. PRINCIPLES

**KEY POINTS:**

- Principles for identifying Pacific salmon LRPs are adapted from national guidance on LRPs.
- **Principle 1.** LRPs should be selected based on the best available information.
- **Principle 2.** LRPs should be consistent with the goal of avoiding serious harm.
- **Principle 3.** LRPs should be operational, i.e., feasible to calculate and relevant to policy and management.
- **Principle 4.** LRPs should be reliably estimable and plausible.
- **Principle 5.** When selecting among multiple methods for determining LRPs, the choice should take into account uncertainty.
- **Principle 6.** Pacific salmon LRPs should be consistent with the goals and objectives of the WSP.
- These principles are intended to guide our approach for developing Pacific salmon LRPs while providing flexibility due to differences in local biological characteristics, data qualities and data quantities, among salmon species and stocks.

Here we outline principles for developing LRPs for Pacific salmon, adapted from those developed for national-level guidance on LRPs (Marentette et al. In prep.). That guidance allows for flexibility in the development of LRPs to respect differences in species life-histories and data types, quantities, and qualities, and is not meant to be prescriptive. By following similar principles, Pacific salmon LRPs are aligned with national direction.

**Principle 1**. LRPs should be selected based on the best available information for the SMU, including evidence of serious harm, data and knowledge informing underlying biological processes, Indigenous Knowledge, and comparison with similar SMUs (Marentette et al. In prep.). Criteria for evaluating best scientific information developed for US National Standards may be applicable here ("US Code of Federal Regulations" 2021). These criteria are: relevance, inclusiveness, objectivity, transparency and openness, timeliness, verification and validation, and peer review. In addition, scientific information should include an evaluation of uncertainties and identify gaps in our understanding or information. When uncertainty exists in identifying the most appropriate approach to define an LRP, these uncertainties should be acknowledged and considered when providing LRP recommendations. Where the weight-of-evidence supports a set of assumptions or hypotheses associated with a candidate LRP, then this LRP can be recommended. Where evidence is inconclusive, this uncertainty should be integrated into the estimation of status and the uncertainties should be clearly communicated.

Within this principle, it is recognized that science is not static and new findings continually advance our understanding of best available information. In particular, peer-review is necessary to ensure that the quality and credibility of data and methods for LRP development meet the standards of the scientific community. When determining whether to conduct a peer review, the level of novelty and complexity, and any previous peer-reviewed stock assessments, should be considered. Although routine updates may not need formal peer review, new LRPs or the application of benchmarks and LRPs to new CUs and SMUs may require peer review.

Similarly, best practices, or practices that have been demonstrated to work well, can be used to inform reference points, as defined by Sainsbury (2008): "The 'best practice' concept is based on the best practice that has been demonstrated through use, and recognizes that views of what is 'best' will continuously improve with experience. Best practice is not an absolute or fixed entity, or a guarantee of adequacy. It is based on experience to date and it is expected to evolve over time."

**Principle 2**. LRPs should be consistent with the goal of avoiding serious harm to the SMU, as described in DFO (2009a) and Section 1 of this paper. The LRP should be set above the level where serious harm occurs and should avoid long-term losses that may accompany such undesirable states, such as those related to fishing and ecosystem components, e.g., dependent predators (DFO 2009a, 2009b). In addition, LRPs should be representative of the entire SMU. In cases where only components of an SMU are monitored (e.g., CUs), the monitored component can be used to assess SMU status when it is thought to represent the entire SMU (Section 5).

**Principle 3**. LRPs should be operational. They should be feasible to calculate based on data that are available and relevant to the policy context and management of fisheries on SMUs. Data availability varies widely among CUs and SMUs, requiring a variety of approaches for CU and SMU-level assessments. No one method will be operational across all cases. Also, it is beneficial if LRPs are easy to communicate to managers, First Nations, and stakeholders in a way that informs decisions at time-scales relevant to management. Other operational considerations are cost-effectiveness and simplicity in understanding.

**Principle 4**. LRPs should be reliably estimated. To the extent possible, LRPs should indicate a level above where serious harm occurs with acceptable accuracy and precision, instead of capturing random noise or observation errors. Reliable estimation will depend on the quality and frequency of data collection, model specification, and the evidence to support underlying relationships and population dynamics used to derive LRPs. Reliability can be addressed by checking the sensitivity of LRPs to uncertainties in underlying data, models, or assumptions via sensitivity analyses or simulation-evaluation, or simply by assessing plausibility given biological or life-history information about the SMU (Marentette et al. In prep.).

LRPs can be derived using multiple analytical approaches. If LRPs cannot be estimated reliably using one method or approach, then it is advisable to consider alternative approaches based on different sets of assumptions and/or data. When LRP estimates converge using different approaches, this increases support that the methods capture underlying population dynamics despite differing assumptions and use of available data.

Where possible, a statistically integrated approach for estimating LRPs should be considered in order to propagate uncertainties throughout analyses and to be consistent with current best practices in fisheries stock assessments (Punt et al. 2020). Staton et al. (2017) and DeFilippo et al. (2021) provide recent examples of integrated models used for salmon assessments. Both studies show that uncertainty propagation increases realism of model estimates and associated uncertainty. However, Staton et al. (2017) demonstrated that similar point estimates of current status can be achieved by using sequential estimation approaches and the benefits of statistically integrated approaches may not be large enough to warrant an integrated analysis in all cases.

**Principle 5**. When selecting among multiple methods for defining LRPs, the choice should take into account uncertainty. Candidate methods for LRPs vary in how and the extent to which they account for uncertainty in underlying data, modelled population dynamics (parameter assumptions and model structure), and derivation of CU-level statuses. These uncertainties create risks of LRPs providing a misleading threshold of serious harm. All else being equal, methods that rely on high quality data, include fewer assumptions, and explicitly account for underlying uncertainties should be preferred.

When considering LRPs under alternative model assumptions, LRPs can be chosen based on strength of evidence for underlying assumptions or averaged when alternative assumptions are equally plausible. Further, the sensitivity of LRPs to various underlying model assumptions or data qualities and quantities can be evaluated in simulation, where LRPs that are less sensitive to key uncertainties would be preferred.

**Principle 6**. In addition to principles derived for marine species in general (Principles 1-5) and to meet the goal of avoiding serious harm under DFO's Precautionary Approach Policy (Principle 2), Pacific salmon LRPs should be consistent with the goals and objectives of the WSP. The WSP requires both the definition of biological units and an assessment of their status along biological metrics, with lower benchmarks used to represent the level that avoids risk of extinction. This approach is consistent with avoiding serious harm to the CU. Above the lower benchmarks (above Red status), irreversible or slowly reversible impacts are avoided. Ignoring CU-level status by focusing solely on SMU-level status can result in serial depletion (or loss) of weak component CUs within an SMU, resulting in a possibly misleading indication status and serious harm. Therefore, to be consistent with the WSP, LRPs should consider status of component CUs.

## 3.2. APPLYING THE PRINCIPLES TO LRP DEVELOPMENT

Our goal is to provide overall guidelines on LRP development following the principles listed above while providing flexibility due to differences in biological characteristics and types, qualities and quantities of data among Pacific salmon species and SMUs. We indicate the extent to which candidate LRP methods proposed here are aligned with these principles. Additional LRP methods may be developed in the future to capture a broader range of data availability, quality, and types, and/or dimensions of biological status; the development of these additional methods should be aligned with the key principles summarized here.

In the next section, methods for estimating CU status are described, as implemented in previous status assessments under the WSP, and candidate LRPs are proposed. Guidelines on how to choose among LRPs is described in Section 5.

# 4. PROPOSED LRP METHODS FOR PACIFIC SALMON

LRP methods require assessments of status at the scale of CUs. Abundance data required for CU assessments are sometimes influenced by hatchery enhancement, which requires additional considerations. This section includes recommended methods to derive CU-level statuses and estimates LRPs. Within CU status assessments, we first describe our approach for accounting for hatchery enhancement.

## 4.1. CONTRIBUTION OF HATCHERIES

**KEY POINTS:**

- While hatcheries are a useful tool for augmenting production for harvest and conservation, they can reduce wild genetic diversity and fitness and are considered a risk factor for the long-term persistence of CUs.
- Salmon that are enhanced by hatcheries are not considered 'wild' under the Wild Salmon Policy and are not usually included in assessments of biological status.
- The data used to assess the contribution of hatcheries to spawning are associated with high uncertainties related to the tagging method used, sampling rates, uncertainty in survival of natural vs. hatchery-origin fish, and observation errors.
- Populations dominated by wild fish but influenced by hatchery strays from outside of the basin are generally included in CU assessments, but these strays may bias estimates of natural production and resulting assessments.
- Following previous WSP status assessments, when data are available, the demographic influence of hatchery production can be removed from time-series of abundances. This step applies to populations included in analyses, after removing populations with high hatchery influence. Where data to differentiate hatchery- from natural-origin spawners are not available, total spawner abundances include hatchery-origin fish, representing a key source of uncertainty for hatchery-influenced populations.
- Methods to process data on hatchery contributions within assessments and guidance on best practices within DFO continue to evolve.

Hatcheries contribute to spawning abundances of many salmon populations and can be used as a conservation tool as well as a way to increase the availability of fish for harvest. Hatcheries can also reduce wild genetic diversity and fitness, defined as adult-to-adult reproductive success, and are considered a risk factor for the long-term persistence of CUs (Withler et al. 2018). Salmon that are hatchery-origin, as well as their progeny, are not considered 'wild' under the Wild Salmon Policy. Typically, only populations dominated by wild salmon are included in assessments of biological status. However, separating out the influence of hatcheries in time-series of spawner abundances and recruitment is challenging, in part because hatchery-origin salmon are often not marked, e.g., with fin clips or fish tags, and so are indistinguishable from natural-origin spawners. Also, many salmon escapement programs, such as those where salmon spawners are counted from helicopters (Parken et al. 2003) do not have biological sampling programs to collect, mark and tag data from individual salmon.

### 4.1.1. Accounting for genetic risks of hatchery production

Following Withler et al. (2018), we recommend including only populations without significant hatchery enhancement in analyses of CU and SMU biological status consistent with the WSP. Proportionate Natural Influence, PNI, is a metric of the genetic risk of hatcheries on natural populations, with values $< 0.5$ indicating integrated-hatchery populations, where more than half of spawners are hatchery origin, values $\geqslant 0.5$ and $< 0.72$ indicating integrated-transition populations where natural-origin fish predominate, and values $\geqslant 0.72$ indicating integrated-wild populations, where more than half of spawners are considered 'wild' under the WSP (Withler et al. 2018). While these guidelines were proposed for Chinook Salmon where hatchery enhancement is most common, they are also applicable to other salmon species (Withler et al. 2018).

*Table 1. Potential guidelines for the implementation of integrated hatchery populations in WSP assessments based on their biological designation and Proportionate Natural Influence, PNI, taken from Withler et al. (2018).*

| Designation | PNI | Inclusion in WSP assessments |
|---|---|---|
| Wild | na | Yes |
| Wild-stray influenced | na | Provisional |
| Integrated-wild | $\geq 0.72$ | Yes |
| Integrated-transition | $\geq 0.5$, $< 0.72$ | Provisional |
| Integrated-hatchery | $< 0.5$ | No |

When assessing population status, Withler et al. (2018) recommend the inclusion of integrated-wild populations within biological assessments under the WSP, and provisionally, integrated-transition populations (i.e., PNI $\geqslant 0.5$ ). Accordingly, only populations with PNI values $\geqslant 0.5$ were included in the assessment of CU and SMU status in our case study applications. Stricter definitions of hatchery enhancement can be considered by including only populations with PNI values $\geqslant 0.72$. In practice, applying this stricter threshold for our case study on Chinook Salmon resulted in excluding most data since reliable time-series of PNI values and spawner abundances are only available for exploitation-rate indicator populations, which tend to be populations with hatcheries. Adopting a threshold of $\geqslant 0.5$, a level associated with more than half of spawners being natural origin, was the result of a trade-off between assessing remaining CU-level biodiversity and excluding significant hatchery impacts. For some populations, early periods of high enhancement can be removed from time-series and assessments can focus on recent periods without significant enhancement (Grant et al. 2012). For hatcheries aimed at rebuilding critically depleted populations, production may be dominated by hatchery-origin fish for a period until abundances are above lower conservation thresholds. Guidelines on the assessment and management of these conservation hatcheries are currently being developed by DFO's Salmonid Enhancement Program, including regular assessments of the proportion of hatchery-origin spawning.

Data used to assess hatchery contribution to spawning and estimate PNI values are associated with high uncertainties. For our case study on Chinook Salmon, proportions of hatchery-origin spawners were determined from spawning ground surveys for thermal marking on hatchery-origin salmon. When data on thermal marking were not available, coded-wire tags (CWTs) were used to identify hatchery-origin spawners, but were associated with increased uncertainty. Large interannual variability in the proportion of hatchery-origin spawners can result from natural variability in survival of hatchery- versus natural-origin spawners, low sampling rates for hatchery-origin spawners, and high observation errors, requiring decisions about temporal averaging. For the westcoast Vancouver Island Chinook case study, we averaged over the available time series where hatchery objectives have remained constant, though recommend further research quantifying the sources of uncertainties and evaluating the sensitivity of results to various time periods for averaging (e.g., recent generation versus entire time period).

In addition to guidance on biological assessments under the WSP, Withler et al. (2018) further recommend developing biological goals for hatchery-influenced populations and documenting trade-offs between increased genetic risk to wild populations from hatchery production and increased abundance required to support other objectives. Enhancement plans are being developed for hatchery-influenced populations by DFO's Salmonid Enhancement Program, which include objectives related to PNI, harvest, assessment, and stewardship and measures to achieve objectives. Once developed, enhancement plans can be integrated with harvest and habitat planning within integrated management and/or rebuilding plans. Guidelines and methods for estimating PNI values are also being documented by DFO's Salmonid Enhancement Program (DFO, In prep.)[3].

### 4.1.2. Wild populations influenced by straying from hatcheries

In addition, Withler et al. (2018) recommend that populations dominated by wild fish but influenced by hatchery stays (called 'wild stray-influenced' populations) should be included in CU assessments under the WSP. These populations receive strays from out-of-basin hatchery programs, but do not contain hatcheries themselves. Although the majority of fish may be wild in these populations, one-way gene flow modelling suggests that over time PNI values will decline to levels consistent with hatchery-dominated systems with continued straying. In practice, straying from out-of-basin hatcheries and the genetic impacts are generally not monitored or assessed, and so out-of-basin strays are included in total abundances within biological assessments. However, this represents a gap in our knowledge of hatchery impacts and our ability to implement recommendations from Withler et al. (2018). Two exceptions are Candy and Beacham (2000) which describes patterns of straying of Chinook salmon in the Fraser watershed and Vancouver Island, and more thoroughly on the west coast of Vancouver Island where studies estimating the extent of straying for Chinook Salmon are on-going and may inform the evaluation of hatchery impacts in future biological assessments (W. Luedke pers. comm.).

### 4.1.3. Removing the demographic influence of hatchery production

For some WSP assessments that include integrated-transition and integrated-wild populations, the demographic influence of hatchery production is removed from time-series of abundances when data on the proportion of hatchery- versus natural-origin fish on the spawning grounds

[3]DFO. Guidelines for Calculating the Proportionate Natural Influence Index as a Metric of the Genetic Influence of Enhanced Pacific Salmon on Wild Populations. Report of the Salmonid Enhancement Program, Vancouver, BC. In prep.

are available (e.g., from marking of hatchery-origin fish or other data on the relative survival of hatchery-origin fish, DFO 2015). Specifically, the contribution of hatchery-origin production is removed from both the benchmark estimation and metric of spawner abundance. For stock-recruitment based benchmarks, the contribution of hatchery-origin fish is removed from recruitment estimates but not escapement, as it is assumed that all natural spawners reproduce successfully in the wild and contribute to natural production. This way, the spawner-recruitment relationship represents the production derived from spawners in the natural environment. For the metric of spawner abundances, the contribution of hatchery-origin fish can be removed from spawner time series to reduce the influence of variability in annual hatchery production on status (DFO 2015). Although removing hatchery-origin fish from analyses is inconsistent with the recommendation of Withler et al. (2018) to include all spawners in biological assessments when natural spawning predominates (PNI $\geqslant$ 0.5), it is consistent with existing published WSP assessments on which our analyses relied and developing new time-series was beyond the scope of this study.

In most cases where hatchery-origin fish are not marked or sampled on the spawning grounds, data on the proportion of hatchery-origin spawners are not available. In these cases, WSP assessments generally rely on total spawner abundances including hatchery contribution, as long as spawner abundances are believed to be predominantly natural origin (e.g., PNI $\geqslant$ 0.5) (e.g., Southern BC Chinook Salmon, DFO 2016b), aligned with recommendations of Withler et al. (2018). In these cases, there may a risk of current status being confounded by hatchery production which may mask changes in natural production and obscure inferences for unenhanced populations in the CU. This risk is partly mediated but not eliminated by removing populations that are dominated by hatchery-origin fish from assessments. In general, we recommend flexibility in addressing hatchery-influenced populations in assessments as methods to process hatchery-origin fish and associated guidance evolve.

## 4.2. ESTIMATION OF CU STATUS

**KEY POINTS:**

- We recommend that CU-level status consider multiple metrics, either integrated through formal status assessments or through the **Pacific Salmon Status Scanner tool**, also called the Salmon Scanner.
- The Salmon Scanner provides status from a composite of metrics and benchmarks on spawner abundances, and long- and short-term trends in spawner abundances.
- Various benchmarks on spawner abundances have been identified to account for differences in data types, quantities and qualities among CUs, including those based on stock-recruitment relationships, percentiles of historical spawner abundances and freshwater spawning and rearing capacity.
- Distributional metrics of spawning have been included in formal WSP assessments.
- For the purposes of LRP development, CU statuses were derived in two ways: using multiple metrics applied within the Salmon Scanner and a single metric on spawner abundances to demonstrate the consistency in these approaches and highlight any differences.

To be consistent with the multidimensional approach to WSP status assessments described in Holt et al. (2009), we recommend that CU-level status consider multiple metrics, either integrated through formal status assessments (Grant and Pestal 2013; DFO 2015; DFO 2016b; Grant et al. 2020a) or through other multidimensional approaches like the Pacific Salmon Status Scanner

(Pestal et al. In prep.). In our case study applications Holt et al. (2023), we demonstrate the application of the Pacific Salmon Status Scanner tool as a way to rapidly approximate more detailed WSP status assessments. The Salmon Scanner (i) estimates statuses for individual WSP metrics and (ii) applies a decision tree algorithm to integrate multiple status estimates into a single status estimate (e.g., Red, Amber, Green) based on data type and availability. By using multiple metrics (Table 2), the Salmon Scanner allows for the assessment of status across a wide range of data availabilities. When data for a single metric are not available, other metrics can be used to inform status. The decision tree algorithm was verified with data and local expertise (Pestal et al. In prep.). An expert review of rapid status results for each CU is intended to be incorporated into the application of this tool (S. Grant, pers. comm.). The Salmon Scanner can provide assessments under data limitations, and methods to account for resulting uncertainties from these data limitations are currently being integrated into the Scanner.

*Table 2. Metrics currently used in the Pacific Salmon Status Scanner.*

| Category | Metrics | Example benchmarks (citations demonstrating levels above serious harm) |
|---|---|---|
| Metrics on abundances | Absolute spawner abundances relative to absolute abundance benchmark | 1000 spawners (1,2) |
| | Absolute or index of spawner abundances relative to estimated benchmarks | Sgen (3) or 25th percentile of observed spawner abundances (4) |
| Metrics on trends | Percent change in spawner abundances over the most recent 3 generations | 25 percent decline (1,5) |
| | Ratio of the current generational geometric mean to the geometric mean over the time-series | 0.5 (5,6,7) |

(1) (Mace et al. 2008; COSEWIC 2021); (2) (Cultus Sockeye Recovery Team 2005); (3) (Holt 2009); (4) (Holt et al. 2018); (5) (Holt et al. 2009) (6) (Grant and Pestal 2013); (7) (Porszt et al. 2012)

Various benchmarks on spawner abundances have been identified to account for differences in data types, quantities and qualities among CUs. For data-rich CUs where spawner-recruitment relationships can be reliably estimated, Holt (2009) recommend a lower benchmark at the abundance resulting in recovery to spawner abundances at maximum sustained yield, $S_{MSY}$, in one salmon generation under equilibrium conditions, $S_{gen}$. When applying stock-recruitment analyses, the spatial scale of density dependence should be carefully considered, which may be smaller or larger than the CU. Where recruitment time-series are not available and productivity is assumed to be moderate or high, and harvest rates moderate or low, specified percentiles of observed spawner time-series (e.g., $25^{th}$) can be used as a proxy for spawner-recruitment benchmarks (Holt et al. 2018). For Chinook, Sockeye, and Coho Salmon where production is often limited by the quantity of freshwater habitat, equilibrium spawner abundances can be predicted from habitat characteristics to inform abundance-based benchmarks (Parken et al. 2006; Noble et al. 2015). For example, Parken et al. (2006) use the relationship between watershed area and spawner-recruitment based reference points in a meta-analysis of Chinook Salmon populations from across the Pacific region to predict reference points for Chinook populations without recruitment data. Also, information on freshwater habitat capacity can be used to develop informative priors for stock-recruitment benchmarks estimated with Bayesian techniques (e.g., Atlas et al. (2020) for Sockeye Salmon).

Similarly, metrics and benchmarks on long-term and short-term trends in spawner abundances are included in the Salmon Scanner. Long-term trends are measured by the ratio of recent generational geometric average spawner abundances relative to the long-term geometric average, and short-term trends are measured as the percent change in spawner abundances over 3 generations, the time period used in COSEWIC assessments (Holt 2009). Lower benchmarks on these metrics represent levels below which there is increased risk of extinction (Holt et al. 2009).

In addition, metrics on the distribution of spawning within a CU can be considered in WSP assessments (Peacock and Holt 2010; Peacock and Holt 2012; DFO 2016b), but may not be required for all salmon species and to-date have not been included in the Salmon Scanner. In one example, the distribution of spawners across spawning sites and contractions in that distribution over time were considered in a WSP assessment for southern BC Chinook (DFO 2016b). In addition, recovery targets for Interior Fraser Coho account for the distribution of spawners among sub-populations (Interior Fraser Coho Recovery Team 2006). One challenge to applying metrics on distribution is identifying benchmarks that distinguish populations with increased risk of extinction.

For the purposes of LRP development, CU statuses for case study applications were derived in two ways, using the multiple metrics applied within the Salmon Scanner and a single metric on spawner abundances. We applied both to demonstrate the consistency in these approaches and highlight any differences. When only a single metric is applied to derive status, there is a risk of providing a misleading assessment if other metrics that would have been used in a multidimensional approach provide contrary information, but are not included. A full review of the Salmon Scanner will be provided in Pestal et al. (In prep.).

## 4.3. LRP ESTIMATION

**KEY POINTS:**

- **CU status-based LRPs** are calculated from the proportion of CUs within an SMU that are assessed as being above Red status, with 100% as the recommended LRP.
- CU status-based LRPs are recommended as the default approach for estimating LRPs for Pacific salmon and triggering rebuilding plans under the *Fisheries Act*.
- LRPs along a gradient of aggregate SMU-level abundances (**'aggregate abundance LRPs'**) may be required for fisheries management decisions at the SMU scale, and are considered supplemental to CU status-based LRPs.
- Two types of aggregate abundance LRPs are identified: **logistic regression LRPs** and **projection LRPs**.
    - Both rely on the relationship between observed aggregate abundances and statuses of component CUs, but logistic regression LRPs rely on empirical data directly whereas projection LRPs are derived from projections of CU-level population dynamics, usually parameterized from empirical data.
    - Both aggregate abundance LRPs are probabilistic in nature, identifying the aggregate abundances associated with an acceptable probability of all CUs achieving status above Red.
- An assumption of the logistic regression LRPs is that the relationship between aggregate abundance and CU-level status observed historically represents the current (and future) relationship. If the covariance in population dynamics among CUs is non-stationary, logistic regression LRPs may not represent levels above serious harm.
- Projection LRPs can integrate plausible ranges of parameter uncertainties that may differ from those observed historically, unlike logistic regression LRPs.

In this section, LRPs that integrate statuses of component CUs are proposed. These LRPs fall into two categories: those based on the proportion of component CUs above the Red zone, called CU status-based LRPs, and those based on aggregate abundances, called aggregate abundance LRPs. Aggregate abundance LRPs are further subdivided into logistic regression LRPs and projection LRPs (Fig. 2). A more detailed description of LRPs is included in Holt et al. (2023).

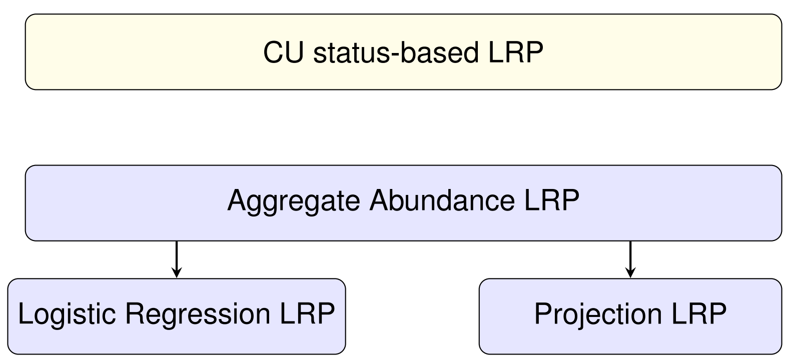


*Figure 2. Types of LRPs for Pacific Salmon, showing the nested nature of logistic regression and projection LRPs within the category of aggregate abundance LRPs.*

#### 4.3.1. CU status-based LRPs

CU status-based LRPs are calculated from the proportion of CUs within an SMU that are assessed as being above Red status (Fig. 3). To be consistent with the intent of the WSP to preserve biodiversity at the CU-level, we identify an LRP at 100% of CUs having status above Red (i.e., either Amber or Green). See Section 5 for a step-wise approach for identifying LRPs that further considers data limitations when identifying the proportion of CUs above the Red zone, and Section 6 for a description of associated uncertainties. CU statuses are derived using the approaches described in Section 4.2, and are submitted to peer review, as described in Section 5.

*Alignment with LRP Principles*

CU status-based LRPs can be based on the best available information (Principle 1) by incorporating multiple dimensions of status through formal, peer-reviewed WSP status assessments or the use of the Salmon Scanner with peer review. By using status derived from the annual implementation of the Salmon Scanner, relevant and timely information is used to inform status in a way that is transparent and open. CU status-based LRPs represent serious harm (Principle 2) as indicated by the status of any one component CU within the SMU being in the Red zone under the WSP, given that the deterioration of stock structure (i.e., loss of diversity) can itself be a form of serious harm. CU status-based LRPs are operational (Principle 3) because they are simple to calculate and communicate as a proportion of CU statuses. For SMUs where harvest is managed at the aggregate SMU scale, however, CU status-based LRPs are not easily incorporated into harvest control rules at that scale. Reliability of estimation (Principle 4) depends in part on the underlying data and is CU- and SMU-dependent. Uncertainties are not currently propagated from CU-level benchmarks and statuses from the Salmon Scanner, to LRPs and SMU statuses (Principle 5). CU status-based LRPs are well aligned with Principle 6, being derived directly from WSP metrics of status for CUs.

A further advantage of this method is that it can easily be extended to other spatial scales under which Pacific salmon are managed. For example, CUs can be assessed individually when threats and responses are localized to specific watersheds, e.g., Cultus Sockeye which has unique threats to its spawning and rearing habitats. CU status can also be aggregated at various scales and across species when threats and responses are broader, e.g., for the management of numerous salmon species and CUs impacted by the Big Bar landslide reported in 2019.

In addition to CU status-based LRPs, we developed LRPs along a gradient of aggregate SMU-level abundance accounting for component CU-level statuses. These 'aggregate abundance LRPs' may be required for fisheries management decisions at the SMU scale, but are considered supplemental to CU status-based LRPs for the purposes of the Fish Stocks provisions. We identified two types of aggregate abundance LRPs: (1) logistic regression LRPs and (2) projection LRPs (Fig. 2). Both LRPs rely on the relationship between observed aggregate abundances and statuses of the component CUs, but they differ in that logistic regression LRPs rely on empirical data directly, whereas projection LRPs are derived from projections of CU-level population dynamics usually parameterized from empirical data. Also, both LRPs are probabilistic in nature, identifying the aggregate abundances associated with an acceptable probability of all CUs achieving status above the Red zone. To an extent uncertainty in the underlying relationship between observed aggregate abundances and component CU-level statuses is represented in the probabilistic nature of these LRPs; larger uncertainties result in higher LRP values and vice versa, all else remaining equal. The ability of aggregate-abundance LRPs to reliably represent thresholds of serious harm at the CU level depend on the strength of the underlying relationship between aggregate abundance and CU statuses as inferred from observed data.

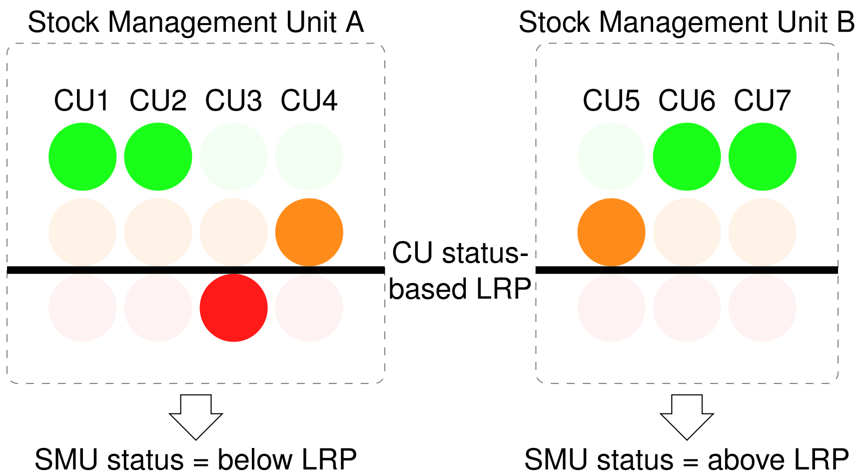


*Figure 3. Schematic of 'CU status-based LRP' applied two example SMUs. 'Stock Management Unit A' (left) consists of four component CUs, of which two are Green status, one is Amber status, and one is Red status. 'Stock Management Unit B' (right) consists of three component CUs of which two are Green status and one is Amber status. 'Stock Management Unit A' would be assessed as below the LRP while 'Stock Management Unit B' would be assessed as above the LRP.*

#### 4.3.2. Aggregate abundance LRPs

**Logistic regression LRPs**

Logistic regression LRPs can be derived from an empirically estimated relationship between CU-level statuses and aggregate SMU abundance. This method extends the CU status-based LRP by identifying the aggregate abundance level that has historically been associated with all component CUs having status above the Red zone, as approximated from status on a single metric of spawner abundances relative to a lower benchmark. For each year of observed data, SMU-level status is quantified as a Bernoulli variable: 1 (success) = all CUs have estimated status greater than the lower benchmark and 0 (failure) = all CUs did not have status greater than the lower benchmark, i.e., at least one CU was assessed below the lower benchmark. A logistic regression is then fit to these outcomes to estimate the probability that all CUs have abundances above their lower benchmarks as a function of aggregate SMU-level spawner abundances. Given the difference in number of component CUs among salmon species (more for Sockeye Salmon than for other species), the likelihood of at least one component CU having Red status is greater for Sockeye. The following logistic regression equation is used to estimate LRPs,

$$\log(\frac{p}{1-p}) = B_0 + B_1 \sum_{i}^{i=nCUs} S_{i,t} \quad (1)$$

where, $p$ is probability, $B_0$ and $B_1$ are estimated logistic regression parameters and $S_{i,t}$ is spawner abundance to CU $i$ in year $t$. Equation 1 is then re-arranged to calculate the LRP as the aggregate spawner abundance associated with the pre-specified probability threshold of $p^*$,

$$LRP = \frac{log(\frac{p^*}{1-p^*}) - B_0}{B_1} \quad (2)$$

An example logistic regression fit is shown in Figure 4, with LRPs associated with four probability thresholds, 0.5, 0.66, 0.90, 0.99, representing minimum levels above which probabilities are more likely than not, likely, very likely, and virtually certain, respectively, as defined by the International Panel on Climate Change, IPCC (Mastrandrea et al. 2010, Table 3). Mastrandrea et al. (2010) also highlight the range 33%-66% as representing 'as likely as not', encompassing probabilities slightly above even (50%-66%). The mid-point at 50% represents an equal probability that all CUs will be above Red status as there is that they will not. An additional consideration in this step is the probability threshold for triggering LRPs described in DFO's Guidelines for the Implementation of Rebuilding Plans (DFO 2021d). These guidelines specify that, "unless otherwise defined in stock-specific precautionary approach frameworks, the LRP should be considered breached if the terminal year stock status indicator is estimated to be at or below the LRP with a greater than 50% probability or if the projected stock status indicator falls below the LRP with a greater than 50% probability under a zero catch scenario in a 1 year projection". While using a 50% probability threshold of one or more CUs having Red status is not directly analogous, in both cases the probability threshold chosen represents the probability of the stock avoiding serious harm.

We recommend positioning LRPs as thresholds with at least a 50% probability of all component CUs being above Red status, but do not recommend a specific probability level above that minimum. Instead, we demonstrate LRPs under various choices of probability levels. Although LRPs are intended to be identified by Science to represent the best scientific estimate of the level below which serious harm is expected to occur (DFO 2021a) and without necessarily introducing additional precaution under uncertainty, there is no scientific basis to choose one probability over others. We distinguish the biological basis of serious harm (any one CU having Red status) from the probability of this occurring, which implies a decision about risk tolerance.

*Table 3. Likelihood definitions adapted from the Intergovernmental Panel on Climate Change.*

| Probability | Definition |
|---|---|
| 33%-66% | range covering, 'about as likely as not' that all CUs are above their lower benchmark |
| 50% | mid-point of the 33%-66% range |
| $>$ 50% | more likely than not that all CUs are above their lower benchmark |
| $>$ 66% | likely that all CUs are above their lower benchmark |
| $>$ 90% | very likely that all CUs are above their lower benchmark |
| $>$ 99% | virtually certain that all CUs are above their lower benchmark |

Uncertainty in logistic regression LRP estimates can be quantified based on confidence or credible intervals on the LRP estimate. See our application to Interior Fraser Coho Salmon for an example Holt et al. (2023). We recommend evaluating the fit of the logistic regression prior to

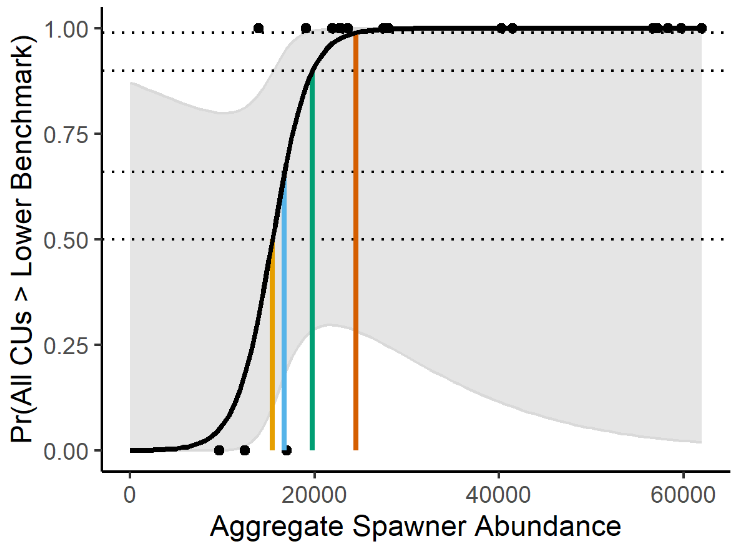


*Figure 4. Logistic regression fit to annual Bernoulli data to predict the probability of all component CUs being above their lower benchmark (LBM) as a function of aggregate SMU abundance. Each black dot represents a year in the observed time series as a Bernoulli indicator showing whether the requirement of all CUs above their lower benchmark, LBM was met (success = 1) or not (failure = 0) as a function of aggregate spawning abundance to the SMU. The black solid line is the maximum likelihood model fit, and the grey shaded region shows the 95% confidence interval around the fit model. Coloured lines illustrate aggregate abundance LRPs for 4 different probability thresholds: p* = 0.5 (yellow), 0.66 (blue), 0.90 (green), and 0.99 (orange) probability that all component CUs are greater than their respective LBM. Horizontal dotted lines intersect the y-axis at each probability threshold, while the solid vertical lines show the corresponding aggregate escapement that will represent the LRP.*

the development of LRPs to identify its reliability in determining serious harm to component CUs. Diagnostics commonly used for logistic regression of Bernoulli distributed data are provided in Holt et al. (2023). For example, diagnostics can evaluate the assumptions that, (a) aggregate abundances are linearly related to log-odds of all CUs being above their lower benchmarks, (b) observations are independent, and (c) there are no influential outliers. In addition, the statistical significance of the predictor variable (aggregate abundance) and the goodness-of-fit of the logistic model can inform its reliability for determining LRPs. Furthermore, the classification accuracy of LRPs developed from a logistic regression can be evaluated on the observed data using a performance metric called the hit ratio. This ratio represents the proportion of successful classifications above or below the logistic regression-derived LRP, relative to the total number classifications or years. Out-of-sample cross-validation methods can also be applied so that model-based LRPs do not include the observed data used for evaluation in this performance metric.

We used a single metric of annual spawner abundances to approximate CU status when using the logistic regression approach, though WSP assessments generally use multiple metrics including trends in abundances and apply generational smoothing. Incorporating metrics on trends and smoothing abundance time-series prior to determining CU status introduces autocorrelation in observed CU statuses, violating the assumption of independent observations in the logistic regression model. This creates a systematic difference in derivation of LRPs depending on how CU status is assessed. Future research could consider logistic regression models that include autocorrelated residuals to develop LRPs based on CU-statuses derived from multiple metrics (e.g., the Pacific Salmon Status Scanner).

One advantage of logistic regression LRPs is that uncertainties in CU-level benchmarks and assessments can be accounted for explicitly. We used a statistically integrated estimation approach, where CU-level stock-recruitment models and associated CU-level benchmarks were estimated in the same model as the logistic regression and LRP derivation. In this way, the uncertainties from CU-level benchmarks and assessments were propagated through to the estimation of the LRP. While Bayesian estimation methods were not applied for the integrated logistic regression approach in any of our case study applications, this extension could be made in the future.

In addition, structural uncertainties in underlying assumptions such as the form of the spawner-recruitment relationship, can be addressed in at least three ways. First, the weight-of-evidence for various assumptions can be evaluated to identify the assumption with the most support, which is then used for LRP development. This can include relying on support for various model forms provided in previous stock assessments or from meta-analyses. Second, various assumptions can be provided as sensitivity analyses demonstrating the impact of assumptions about CU dynamics on LRP estimates and current status. Third, LRPs can be averaged by, for example, combining posterior probability estimates. When averaging, LRPs can be weighted according to the inverse of the variances, the strength of evidence for each hypothesis based on statistical criteria (e.g., AIC), retrospective performance, or expert opinion (Rossi et al. 2019; Jardim et al. 2021). A simple example of model-averaging, in which two alternative models were weighted equally, was demonstrated for projection LRPs in the Interior Fraser Coho case study. When model averaging, it is important to consider the plausibility of various models and the distribution of uncertain parameters (e.g., their variances and biases)(Millar et al. 2015; Dormann et al. 2018). It may be more appropriate to select one model instead of averaging over models when they provide competing hypotheses (i.e., bimodal distributions) with differing management implications (Millar et al. 2015).

#### *Alignment with LRP Principles*

Logistic regression LRPs do not use the best available information for CU statuses in all cases (Principle 1), because they use only one metric of spawner abundances omitting metrics on trends which may be especially informative in data-limited contexts. CUs that do not have abundance-based benchmarks are omitted from consideration of serious harm in this approach even when trends are available to estimate status. Also, logistic regression LRPs approximate CU status by comparing annual spawner abundances to benchmarks instead of generationally smoothed spawner abundances and so may capture random noise in abundance trends instead of true status that is likely autocorrelated over time. In some cases, status based on the single metric on spawner abundances may diverge from that based on multidimensional approaches, e.g., the Pacific Salmon Status Scanner. Logistic regression LRPs are aligned with Principle 2 to the extent that serious harm is indicated by status of any one CU being in the Red zone under the WSP and that the estimated relationship between aggregate abundances and probability of all CUs being above their lower benchmark holds.

Logistic regression LRPs are operational (Principle 3) when harvest management occurs at the aggregate level and requires aggregate abundance LRPs to inform management decisions. However, they are more difficult to communicate being derived from model outputs, and they require the choice of probability of all CUs being above their lower benchmarks, which is difficult to justify from a science perspective.

Reliability of estimation (Principle 4) depends on the reliability of underlying data and the fit of logistic regression as described by model diagnostics. One assumption of this method is that the relationship between aggregate abundance and CU-level status observed historically represents the current (and future) relationship. If the covariance in dynamics among CUs or relative productivities or capacities of CUs are non-stationary, a phenomenon that is increasingly common for Pacific salmon, logistic regression LRPs may not reliably represent serious harm under current or future conditions. Furthermore, LRPs may be unreliable if harvest strategies change over time such that relative exploitation of CUs varies (e.g., due to shifts towards weak stock management or when exploitation varies with the abundance of other species). Uncertainties in CU status are accounted for explicitly when CU- and SMU-level models are statistically integrated, and confidence or credible intervals can provide quantitative measures of estimation uncertainty (Principle 5). Logistic regression LRPs are aligned with Principle 6 to the extent that aggregate abundances are an acceptably reliable predictor of CU level statuses, with the caveat that CU status on a single metric may deviate from the multidimensional approach recommended under the WSP.

**Projection LRPs**

Similar to logistic regression LRPs, projection LRPs rely on the underlying relationship between aggregate abundances and status of component CUs. However, unlike logistic regression LRPs, the aggregate abundance where there is a specified probability of all CUs being above their lower benchmarks is identified from projections instead of directly from historical data.

In this approach, the population dynamics of individual CUs are projected with natural variability in population processes (e.g., recruitment and ages-at-maturity) and with covariance among CUs. Projections are done using current exploitation rates characterized with annual implementation uncertainty. Other exploitation scenarios can also be considered. Projections are run over an initialization period to remove the impacts of starting conditions, and then over multiple generations to identify aggregate abundances characterized by an equilibrium state where the distribution of abundances are stable. Projection LRPs are then estimated using these projected CU abundances to characterize the relationship between aggregate SMU-level spawner abundance and the probability that all CUs exceed their lower benchmarks (e.g., $S_{gen}$). For the SMUs we considered for our case studies, we approximated the management approach with constant exploitation rates with implementation error, though more realistic management procedures that include escapement goals and exploitation limits, or a fixed series of exploitation rates that vary with abundances could be considered in future iterations. As was done for logistic regression LRPs, status was estimated from a single metric rather than from the multidimensional approach within the Salmon Scanner.

One advantage of projection LRPs over logistic regression LRPs is that projections allow for explicit consideration of uncertainty in underlying assumptions about model parameters and the covariance among CUs by including those uncertainties as random components of the projections. Furthermore, unlike logistic regression LRPs, this method is not limited by historical data on CU status. To implement projection LRPs, we adapted a previously developed R package for performing closed-loop simulation modelling, samSim (Holt et al. 2020; Freshwater et al. 2020), as described in the Appendix to Holt et al. (2023) and provided online (see Appendix B).

After providing parameter distributions describing the CU-level population dynamics and exploitation to samSim, the projections included four main steps:

1. Project spawner abundances forward for 30 years after an initialization period and over $nTrial$ stochastic simulations, where $nTrials$ was chosen to stabilize results. In preliminary analyses, we projected over 100 years and found similar results.
2. For each simulated year-trial combination after initialization, characterize abundances as follows:
   - Assign aggregate SMU level spawner abundance for each year-trial combination to an abundance bin based on intervals of 200 fish, e.g., 0:200, 201:400, 401:600, etc.
   - Determine whether all CUs for each year-trial combination were above their CU-level lower benchmarks on abundances, or not.
3. For each aggregate abundance bin, calculate the proportion for year-trial combinations where all CUs were above their lower benchmark relative to all year-trial combinations falling in that bin. These proportions are then plotted against the aggregated abundances for year bin (taken as the mid-point of the bin).
4. Identify the LRP as the mid-point of the aggregate abundance bin with a proportion of CUs above their lower benchmark that is closest to the desired probability threshold (e.g., 0.5, 0.66, 0.9, or 0.99).

Examples of projection LRPs derived from the aggregate abundance of each bin plotted against the proportion of year-trial combinations where all CUs were above their lower benchmark are shown in Figure 5. The choice of 200 fish bins was a trade-off between increasing smoothness of the curve with bins covering smaller range in aggregate abundances and computational limitations of small bins requiring a very large numbers of stochastic simulations to allow for a sufficient number of year-trial combinations within each bin to stabilize results. Also, for our case studies, 200 fish was within the range of uncertainty in observed spawner abundances. Similar to logistic regression LRPs, the uncertainty in CU benchmarks and status are explicitly accounted for in projection LRPs when deriving the probability of all CUs being above their lower benchmarks. However, unlike logistic regression LRPs, there is no estimation uncertainty in projection LRPs because statistical model estimation is not required. Probabilities are derived directly from projections and underlying uncertainties are integrated directly into the overall probability. Therefore, confidence intervals are not provided.

Also, similar to logistic regression based LRPs, structural uncertainty in underlying population dynamics can be considered through sensitivity analyses or model averaging by combining results from stochastic random trials across those structural assumptions. See our implementation for Interior Fraser Coho Salmon in Holt et al. (2023) for more details.

*Alignment with LRP Principles*

As for logistic regression LRPs, projection LRPs use only one metric (annual spawner abundances), and therefore do not necessarily use the best available information (Principle 1) if CU statuses can be estimated using other metrics. Also similar to logistic regression LRPs, projection LRPs represent levels above serious harm (Principle 2) as indicated by status of any one CU being in the Red zone under the WSP, given the projection-based relationship between aggregate abundances and probability of all CUs being above their lower benchmark.

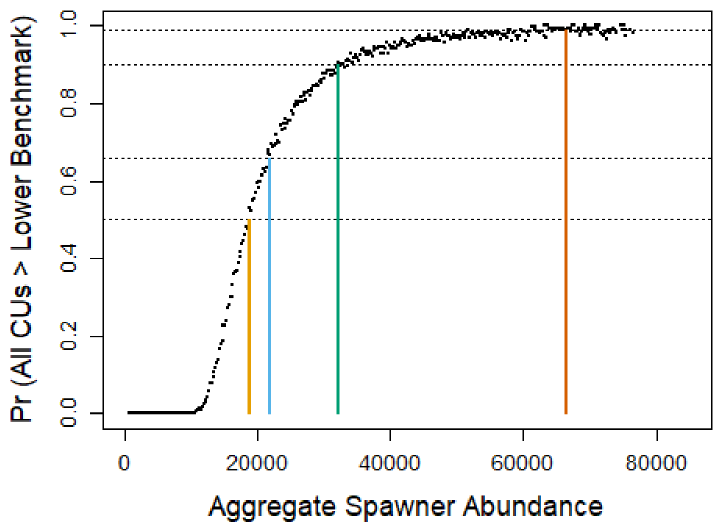


*Figure 5. Example of projected probability curve derived from projections over 30 years and 10,000 MC trials. The curve shows the projected proportions of year-trial combinations where all CUs were above their lower benchmark as a function of aggregate SMU abundance, where aggregate abundances are shown in bins of 200 fish. Each dot in the curve represents a single combination of year and simulation trial. Coloured lines represent candidate LRPs calculated for 4 different probability thresholds, 0.5 (yellow), 0.66 (blue), 0.90 (green), and 0.99 (orange). Horizontal dotted lines intersect the y-axis at each probability threshold, while the solid vertical lines show the corresponding aggregate escapement that represents the LRP.*

Also similar to logistic regression LRPs, projection LRPs are operational (Principle 3) when harvest management occurs at the aggregate SMU level and requires an aggregate abundance LRP to inform decisions. However, this form of LRP may be more difficult to communicate being derived from projections under assumptions of equilibrium, and they require choosing the probability for all CUs being above their lower benchmarks, a choice that is difficult to justify on purely a scientific basis. Reliability of estimation (Principle 4) depends on the underlying parameter distributions and model structure capturing the plausible range of true underlying dynamics. As with logistic regression LRPs, uncertainties can be propagated from CU-level benchmarks and status to LRPs (Principle 5). Unlike logistic regression LRPs though, this method can also integrate plausible ranges or future expectations of parameter and structural uncertainties that may differ from those observed historically. Similar to logistic regression LRPs, projection LRPs are aligned with Principle 6 to the extent that aggregate abundances are a reliable predictor of CU level statuses, with the caveat that CU status on a single metric may deviate from the multidimensional approach recommended under the WSP. Similar to logistic regression-based LRPs, projection-based LRPs are aligned with Principle 6 to the extent that aggregate abundances are able to reliably predict CU-level statuses.

# 5. GUIDELINES FOR APPLYING LRPS

## 5.1. STEPWISE APPROACH FOR SELECTING LRPS

**KEY POINTS:**

- We recommend a step-wise approach for developing LRPs that highlights the important steps, considerations and decisions when identifying LRPs. These steps form our guidelines on the choice and implementation of candidate LRP methods.
- **Step 1.** Compile data
- **Step 2.** Assess CU data deficiencies
- **Step 3.** Evaluate if data-deficient CUs be represented by CUs with data
- **Step 4.** Identify what proportion of CUs above red status (among those with data) is required to avoid serious harm. We recommend 100% as the default.
- **Step 5.** Assess SMU status relative to CU status-based LRP
- **Step 6.** Peer-review status relative to CU status-based LRP
- **Step 7.** Identify if aggregate abundance LRPs are required for fisheries management.
- **Step 8.** If yes, estimate aggregate abundance LRPs and evaluate the extent to which underlying assumptions are met.
- **Step 9.** If yes, apply aggregate abundance LRPs to derive SMU-level status.

We recommend a step-wise approach for identifying LRPs, with the proportion of component CUs with status above Red as the default method (Fig. 6). This is the method recommended to meet the *Fisheries Act* requirement for LRPs, and being based on the biological unit of CU, can be applied to numerous aspects of salmon management, including hatchery, harvest, and habitat management. Aggregate abundance LRPs are presented as an option for cases in which they are required for fisheries management (e.g., locally or internationally), but are considered supplemental to the proportion of CUs with status above Red. The step-wise approach presented below considers data availability for candidate LRP methods and provides guidance when inconsistencies in status occur from applying multiple LRP methods. These steps can be adapted in the future as more methods are developed and/or these methods are further applied and evaluated across additional SMUs and contexts. These steps were developed to be consistent with the principles described in Section 3.

### 5.1.1. Step 1: Data Compilation

The first step is to compile CU-level data to support biological status assessments as described under the WSP (Holt et al. 2009; Holt et al. 2018). These data include (but are not limited to) time-series of spawner abundances, recruitment, hatchery contributions, productivity, and biological benchmarks on spawner abundances. This step generally includes aggregating data at the spawning site or stream level to the CU level.

In some cases, finer spatial scales than CU (e.g., watersheds or sub-populations within CUs) may be considered to define serious harm to an SMU. Although CUs are the population unit of assessment and conservation required under the WSP, the distribution of spawning within CUs (e.g., among watersheds or sub-populations) can be an important component of status (Holt et al. 2009) and these finer scales can be considered when data or supporting information allows. Distribution is a commonly cited component of salmon viability and recovery (McElhany et al. 2000). When applied to the identification of recovery targets for Pacific salmon, Bradford

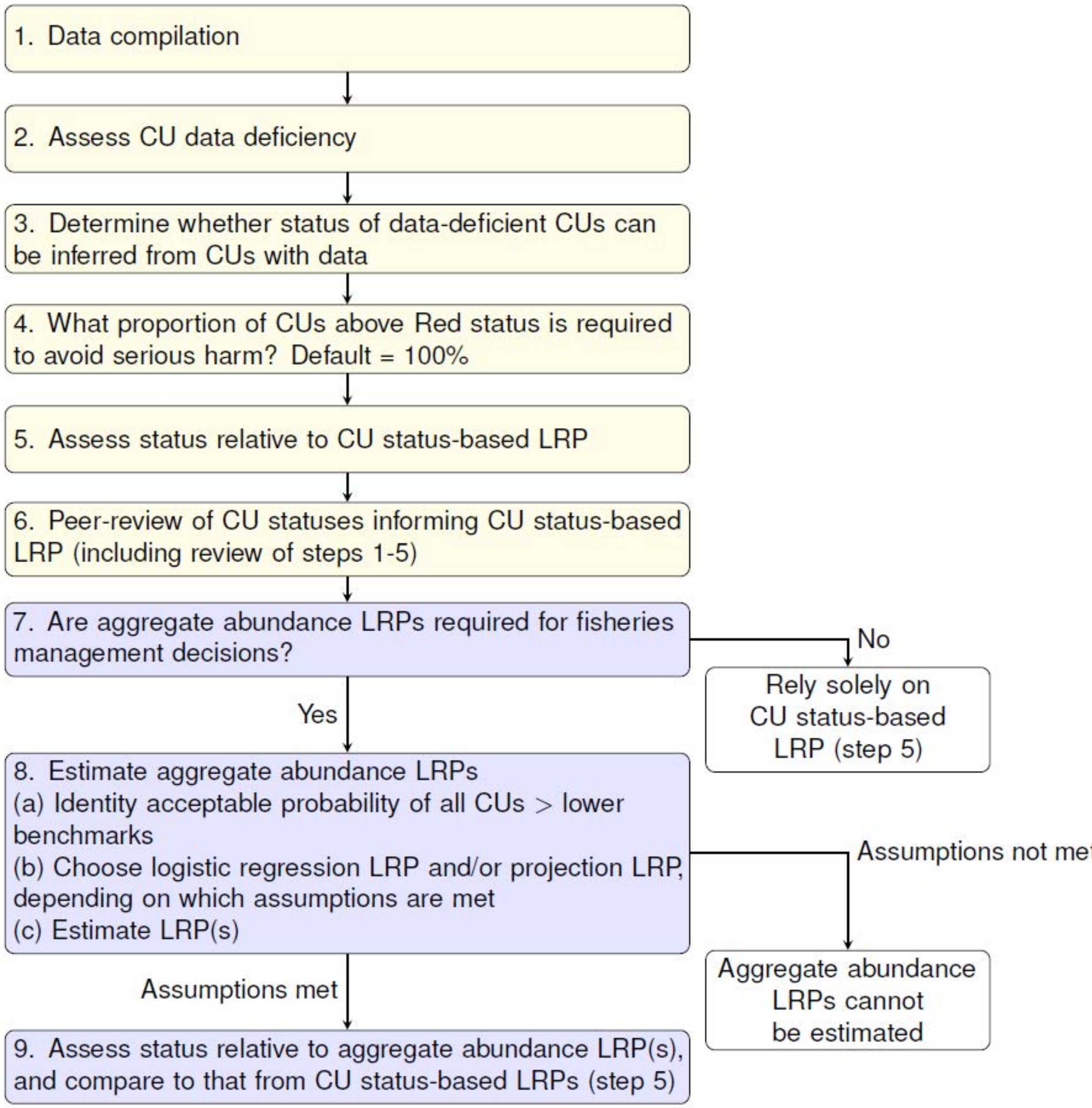


*Figure 6. Steps for setting LRPs and assessing status. Pale yellow boxes indicate those for estimating CU status-based LRPs. Blue boxes indicate those for aggregate abundance LRPs. White boxes indicate when aggregate abundance LRP methods are not recommended.*

and Wood (2004) defined the relevant scale of distribution in units of sub-populations that are demographically independent, where population dynamics of one sub-population is unlikely to affect the dynamics of another. Genetic exchange among sub-populations is expected to occur at greater rates than observed among CUs (or populations), and would likely exceed 10 effective migrants per generation. When applying these criteria to Interior Fraser River Coho salmon, Bradford and Wood (2004) defined sub-populations on the basis of large watersheds or lakes, or partial barriers to migration.

We recommend that the decision on distribution and spatial scale of conservation for biological assessments be part of the peer-review process for CU and SMU assessments, and be based on biological principles of conservation and viability (McElhany et al. 2000; e.g., as reviewed in Bradford and Wood 2004).

Within this step, information on hatchery enhancement is used to identify populations where production is dominated by hatchery-origin fish. These populations (identified by PNI values $<$ 0.5, or expert opinion when data on the proportion of hatchery-origin spawners are not available) are generally excluded from analyses, while those that are dominated by natural-origin fish (e.g., PNI values are $\geqslant$ 0.5), are generally included (Withler et al. 2018). Further, where time-series of the proportion of hatchery-origin salmon on the spawning grounds are available and production is dominated by natural-origin fish, these proportions can be used to generate time-series of natural-origin recruitment for benchmark estimation and natural-origin spawners for status assessment against benchmarks. When the influence of hatchery production is removed in this way, the assessments are less sensitive to the presence of hatcheries and annual variation in hatchery practices.

Infilling among streams or spawning sites for years with missing data is commonly used when compiling CU-level spawner abundance series (e.g., see Grant et al. 2012; Brown et al. 2020). When infilled time series are used to estimate LRPs and monitor stock status relative to LRPs, consideration should be given to the scale at which infilling is done. If LRPs are based on maintaining CU-level diversity, infilling of missing data should generally not be based on escapements from outside of the CU. Infilling among CUs increases uncertainty and may provide misleading status for the CU being infilled, if CUs diverge in status and trends (see Step 3). In addition, hatchery enhancement should be carefully accounted for when infilling to avoid overestimating abundances when infilled numbers are based on sites that are artificially enhanced and when enhancement levels vary during the time series.

#### 5.1.2. Step 2: Assessing CU Data Deficiency

Second, CUs with data to support biological assessments are identified; those without sufficient data are considered data deficient. CUs are assessed based on a variety of metrics including abundances and trends, and data requirements for these metrics vary. At a minimum, a CU must have an index of spawner abundance time-series. These data can be used to estimate trends over time against benchmarks that are common across CUs (Holt et al. 2009). For short-term trend analyses, data are considered insufficient when they include less than half of available years in the last three generations or are of low quality representing only presence/absence. These criteria for trend detection are similar to criteria described in Brown et al. (2020) and applied to spawning sites of Chinook Salmon in Southern BC.

In addition, current spawner abundances can be compared to abundance-based benchmarks, where current spawner abundances are generally defined as the geometric average spawner abundances over the most recent generation. For this metric, at least one year of spawner abundances is required in the current generation to compare against benchmarks. CU-specific benchmarks on spawner abundances can be derived from spawner-recruitment models, percentiles of spawner time-series, or habitat characteristics. Data requirements for benchmark estimation on spawner abundances differ according to the methods applied and are not explicitly defined here. Local biological expertise is required to review available data and benchmarks prior to assessments to identify data deficiencies. For example, changes in environmental conditions over time may result in historical data that are no longer representative of current conditions, resulting in data deficiencies.

#### 5.1.3. Step 3: Determine whether status of data-deficient CUs can be inferred from CUs with data

Third, the extent to which status of data deficient CUs can be inferred from CUs with data is evaluated. By definition, data deficient CUs do not have data on population dynamics to rigorously evaluate the extent to which other CUs with data could be used to represent their status, though information on threats and biological characteristics may be available. To infer status for data deficient CUs, at a minimum we recommend providing evidence that: (i) the threats impacting data deficient CUs are likely to be the same as for CUs with data and their magnitudes are similar, (ii) dominant environmental drivers are similar among CUs, e.g., as reflected by the distribution of CUs across freshwater and marine ecosystems, (iii) biological characteristics, such as life-history type and dominant age-at-maturity of data-deficient CUs are represented in the CUs with data, and (iv) the carrying capacity of data deficient CUs is likely in the range of those represented by CUs with data. Evidence supporting these criteria should be clearly documented and reviewed by local experts. The burden of proof is to identify that data deficient CUs have similar properties to neighbouring CUs, with the default assumption that each CU represents unique biodiversity whose status and trends cannot be represented by other CUs. We provide an overview of the four criteria in Table 4 and describe each one in more detail below.

*Table 4. Criteria to evaluate CU representativeness within SMUs.*

| Criteria | Rationale | Example characteristics | Example sources of information |
|---|---|---|---|
| Threats | CU-specific threats may impact survival rates, growth, and/or reproductive success and therefore statuses and trends | Ecosystem modifications including water extraction, forestry, fires, agriculture, and development, fishing, pollution, aquaculture, and genetic impacts from hatcheries | Published threats and habitat assessments by CU |
| Environmental drivers | CU-specific climatic conditions may impact survival, growth, maturation, or reproductive success and hence status and trends, either due to environmental drivers themselves or the interaction of different environments with common anthropogenic threats | Freshwater: river gradient, connectivity, macroclimate of spawning and rearing habitat, hydrological regime (e.g., (1) for Chinook Salmon). Marine: upwelling, currents, productivity of nearshore environment at ocean entry | Distribution of Freshwater and and Marine Adaptive Zones (2), biogeolclimatic zones describing macroclimates, as in (3), habitat characteristics provided in CU-specific stock assessments, Indigenous Knowledge |

| Criteria | Rationale | Example characteristics | Example sources of information |
|---|---|---|---|
| Life-history characteristics | CUs with the same life-history characteristics such as age-at-ocean-entry are more likely to overlap in spatial and temporal distribution and therefore respond similarly to common threats and environmental drivers compared to those with divergent characteristics | Life-history type (stream vs ocean for Chinook Salmon), age-at-ocean entry, age-at-return, migration timing | CU-specific biological information from stock assessments, Indigenous Knowledge |
| Carrying capacity | Population size is related to the probability of dropping below critical conservation thresholds and hence vulnerability to threats and/or random perturbations | Spawner abundances | CU-specific biological information from stock assessments, watershed size (4), Indigenous Knowledge |

(1) (Beechie et al. 2006) (2) (Holtby and Ciruna 2007) (3) (Medinger and Pojar 1991) (4) (Parken et al. 2006)

**Threats** are defined here as any human activity or process that causes harm, death, or behavioural changes to a species, or the destruction, degradation, and/or impairment of its habitat, to the extent that population-level effects occur (DFO 2014). CUs that are exposed to different threats in freshwater and marine environment within an SMU may diverge in biological characteristics such as survival, growth, and reproductive success and therefore statuses and trends.

CUs can vary in their exposure to **environmental conditions**, related to variability in freshwater and marine ecosystems, macroclimate, and hydrology within an SMU. Although SMUs are usually defined to be spatially cohesive groups of CUs, differences in environmental conditions among neighbouring CUs can result in differences in status and trends.

CUs with similar **life-history characteristics** are more likely to respond to common threats and environmental drivers in the same way compared to those with divergent characteristics. Differences in life-history characteristics have evolved among CUs as a consequence of exposure to different environmental conditions and food availability (e.g., Bourret et al. 2016). In some cases, SMUs have been defined to align CUs with similar life-histories (e.g., Fraser Chinook where SMUs are defined in part based on dominant ages at maturity and adult run timing). In other SMUs, CUs with various life-history types are combined based on their geographic location (e.g., the Mainland Inlet Chinook SMU which contains CUs with ocean- and stream-type fish).

CUs with different **carrying capacities** may respond differently to similar threats. For example, very small CUs may be more vulnerable to moderate fishing pressure if abundances decline below critical conservation thresholds (e.g., 1500 fish, an abundance threshold within the Pacific Salmon Status Scanner), whereas larger CUs may be more resilient to common threats.

Covariation in intrinsic productivity is well documented among spatially proximate populations across Pacific salmon species (Peterman et al. 1998; Pyper et al. 2002; Dorner et al. 2018), providing some support for the use of data-rich CUs to inform CUs without data. In a meta-analysis of spawner time-series across Pacific salmon species throughout BC using data extracted from the Pacific Salmon Explorer Tool (Pacific Salmon Foundation 2020), pairwise correlations in spawner abundances among CUs within SMUs tended to be positive (Appendix C, Fig. C.1).

Overall, we suggest caution when representing SMU status with only a subset of CUs, and recommend evaluating and documenting the risks of incorrectly assigning status of data deficient CUs based on neighboring CUs. We also recommend further quantitative evaluation of these criteria using empirical data disaggregated into groups of CUs with similar environmental conditions, life-history types and management intensity, among other variables. These criteria are not meant to be prescriptive, but are intended to provide general guidelines for drawing inference for data deficient CUs.

If data-deficient CUs do not meet the criteria for inference from the remaining CUs within an SMU, we recommend collection of CU-level data to inform biological assessments. Data collection would therefore be prioritized for CUs that diverge in threats, environmental drivers, life-history characteristics and/or carrying capacities from neighbouring CUs.

#### 5.1.4. Step 4: What proportion of CUs above red status is required to avoid serious harm?

In order to apply CU status-based LRPs, a lower limit on the proportion of CUs above Red status needs to be defined. DFO (2009a) indicates that LRPs are based on biological criteria identified by Science, independent of management processes. Given the goal of the WSP is to protect the biodiversity of Pacific salmon in part by maintaining CUs above lower biological benchmarks, we have identified a threshold of 100% of CUs above Red status as an LRP that will avoid serious harm. Exceptions to this LRP may occur where there is uncertainty or misidentification in the delineation of CUs (e.g., as for some transboundary CUs, Holtby and Ciruna 2007) or CUs are designated extinct. Those CUs would be omitted from the total number of (extant) CUs within the SMU.

This step omits decisions about how to prioritize CUs for conservation given variability in their capacity to rebuild. For some CUs the potential for rebuilding to above the Red zone may be extremely low due to natural conditions or anthropogenic threats. For example, some CUs are naturally more vulnerable to threats because of their biological characteristics (e.g., limited habitat availability) placing them in the Red zone. However, that natural vulnerability does not diminish the serious harm associated with the biodiversity loss if that CU is lost. Rebuilding may also be limited due anthropogenic threats such as climate change. Recent vulnerability assessments indicate that many salmon populations will not be resilient to climate change in the coming decades (Crozier et al. 2019, 2021). These considerations can be identified in rebuilding potential analyses to inform decisions about where resources should be allocated in any subsequent rebuilding plan that is developed (e.g., Carwardine et al. 2019).

Furthermore, unlike many other marine fisheries, threats and management levers for Pacific salmon extend beyond those associated with the fisheries that underlie the definition of SMUs and LRPs. The scale of SMUs is often incongruent with the scale of dominant threats and management levers. As a result, LRPs based on 100% of CUs being above Red status may trigger the development of rebuilding plans under the Fish Stocks provisions when only a component (e.g., a single CU) requires intervention. Furthermore, the most appropriate CU-level interventions may not be related to harvest (e.g., hatcheries or habitat amelioration). Nevertheless, we have identified 100% of CUs within the SMU should be above their benchmarks to avoid serious harm under the Fish Stocks provisions. Triggers and interventions at finer and coarser spatial scales will also be essential to sustain Pacific salmon.

#### 5.1.5. Step 5: Assess status relative to a CU status-based LRP

We recommend CU status-based LRPs as the default approach for identifying LRPs for Pacific salmon. This method provides consistency with assessments previously published under the WSP (Grant and Pestal 2013; DFO 2015; DFO 2016b; Grant et al. 2020a) and allows for the evaluation of status at a hierarchy of scales relevant to salmon rebuilding .

Using this approach, the status of individual CUs is assessed and the proportion of CUs with status above Red is then compared to the LRP identified from Step 4 . Where available, we recommend applying CU assessments from recent peer-reviewed WSP status assessments, in which multiple metrics, such as abundances and short- and long-term trends, are integrated to assign CU status within an expert-driven process (Holt et al. 2009; DFO 2015; DFO 2016b; Grant et al. 2020a). As a general guideline, we suggest that 'recent' should mean within the most recent generation, though major perturbations such as landslide events may make even recent assessments unrepresentative of current status.

Because formal, peer-reviewed WSP status assessments are resources-intensive processes involving large groups of experts over multiple days (Grant and Pestal 2013) and are not available for most CUs, we demonstrate the application of a tool to quickly determine status, the Pacific Salmon Status Scanner (Pestal et al. In prep.). Within this multidimensional framework, CU status depends on a variety of population metrics, where the choice of metrics depends on data availability and may differ among CUs within an SMU. The Salmon Scanner integrates status on available metrics to derive an overall status that is comparable among CUs.

**Status of SMUs with data-deficient CUs**

CU status-based LRPs are considered breached when at least one CU has Red status regardless of whether the status of component data-deficient CUs can be inferred from data-rich CUs or not (Table 5, right column). A single CU with Red status can trigger a rebuilding plan under the Fish Stocks provisions since improved monitoring of data-deficient CUs alone will not result in an increase in SMU status to 100% (all CUs above Red status). Further monitoring of data-deficient CUs is still warranted in this case to inform status of remaining components of the SMU and associated rebuilding efforts.

**Provisional SMU status**

When data deficient CUs are represented by CUs with data we refer to the resulting status as 'provisional' if all CUs included in the assessment are above Red status (Table 5). This status has higher uncertainty and is therefore considered provisional until all component CUs can be assessed directly. In some cases natural variability alone may result in unassessed CUs having Red status even if the criteria listed for CU representativeness in Step 3 are met.

**Data-deficient SMU status**

In contrast, where data deficient CUs are not represented by CUs with data (i.e., criteria in Step 3 are not met), and all CUs included in the assessment are above Red status, then the SMU is considered data deficient and SMU status cannot be evaluated. In this case, we recommend improved monitoring and assessment to fill CU-level assessment gaps.

*Table 5. Guidelines on assessing status for CU status-based LRPs of 100% of CUs being above Red status, when at least one CU is data-deficient*

| | Status of data-rich CUs: all above Red status | Status of data-rich CUs: at least one Red status |
|---|---|---|
| Status of data-deficient CUs can be inferred from data-rich CUs | Provisional SMU status above LRP with high uncertainty | SMU status = below LRP |
| Status of data-deficient CUs *cannot* be inferred from data-rich CUs | SMU Status = data deficient | SMU status = below LRP |

#### 5.1.6. Step 6: Peer-review of status relative to CU status-based LRP

We recommend peer-review of the CU data and assessments used in steps 1 (Data compilation), 2 (Assess CU data deficiency) and 5 (Assess status relative to CU status-based LRP) if CU assessment are developed outside of an existing published, peer-reviewed process. Also, we recommend peer-review of decisions on SMU-scale aggregation from steps 3 (Representation of data-deficient CUs) and 4 (Proportion of CUs required to be above Red status). This peer review can occur, at least in part, through DFO's State of the Salmon Program's annual implementation of the Pacific Salmon Status Scanner. The Salmon Scanner will be applied annually as part of a process integrating outputs with local expertise to provide statuses for CUs. Expert review is required to vet statuses derived from the application of the Salmon Scanner to ensure they are consistent with underlying biological categories given the multiple and sometimes conflicting dimensions of status. The outputs from that process can be the basis for developing CU-level statuses to inform SMU-level LRPs. We emphasize the importance of documented, peer-review of LRPs and status assessments of SMUs prescribed under regulation, either as part the annual application of the Salmon Scanner or in any separate SMU-specific peer-review process. Peer review could be documented, for example, in a CSAS Research Document, CSAS Science Response, and/or CSAS Science Advice Report.

The frequency of SMU-scale peer reviews outside of the annual implementation of the Salmon Scanner will depend on variability in CU-level population dynamics over time and how LRPs and SMU-level assessments are used to inform decision making (e.g., if an SMU is batched under the *Fisheries Act*), among other factors. In the future, management procedures with various frequencies of assessments could be evaluated in a simulation framework to identify risks of delaying assessments relative to costs of implementing them.

### 5.1.7. Step 7: Are aggregate abundance LRPs required for fisheries management?

Although CU status-based LRPs may meet requirements under the Fish Stocks provisions for Pacific salmon, abundance-based LRPs may be needed for fisheries management decisions (Section 2.2). For SMUs where harvest at the aggregate scale is a dominant driver of population dynamics and restricting fisheries harvest is a principal management lever, an LRP along the metric of SMU-level abundances may support precautionary management. For example, when LRPs are used to inform a harvest control rule, fishing pressure can be gradually curtailed as aggregate abundances decline towards the LRP to avoid depletion below that level. Aggregate abundance-based benchmarks may in some cases be required for local or international management. For example, aggregate escapement goals are required for Nass and Skeena Sockeye under Pacific Salmon Treaty provisions (2019), although to comply with WSP objectives, the aggregate escapement goal must consider CU-level diversity.

However, when LRPs are defined within the context of a Management Procedure framework (Section 2.2), then an aggregate abundance LRP may not be required if the framework can demonstrate the probability of individual CUs having status above Red for various management options. For Pacific salmon, management procedures may extend beyond harvest control rules to include time-area closures, gear restrictions, habitat enhancement or hatchery supplementation to protect individual CUs. Therefore, the choice to develop an aggregate abundance LRP depends on the decision context, and should be made in collaboration with various sectors and First Nations responsible for management decisions that affect the SMU. If aggregate abundance LRPs are not required, assessment of the SMU would be provided from steps 1-6. The following steps (8-9) are relevant if aggregate abundance LRPs are required, and build on CU status-based LRPs derived in the previous steps. Uncertainties introduced by the inclusion of models to relate aggregate abundances to CU-level statuses should be considered when choosing LRP methods (Principle 5 in Section 3).

In the context described here, aggregate abundance LRPs are scientifically derived quantities that delineate serious harm to an SMU following the principles outlined in Section 3. In particular, aggregate abundance LRPs are defined to be consistent with the WSP objective of maintaining biodiversity at the scale of CUs. Although these LRPs can inform harvest control rules, harvest management decisions require consideration of multiple objectives beyond those associated with conservation and serious harm (e.g., socioeconomic objectives).

### 5.1.8. Step 8: Estimate aggregate abundance LRPs

#### What is an Acceptable Probability of CU Statuses Being Above Red?

To define aggregate abundance LRPs, first, an acceptable probability of having all component CU statuses above Red is identified. While a 100% or nearly 100% probability of all component CUs being above Red may be desirable from a conservation perspective, inherent uncertainties in population dynamics make this choice impractical. Often, LRPs above the highest observed aggregate spawner abundances are required to achieve a near 100% probability of components being above Red status. Instead, we recommend applying a probability of at least 50% of all CUs being above Red status to align with WSP objectives. As outlined in Section 4, we provide LRPs associated with a range of probabilities, 50%, 66%, 90%, and 99% (where analytically possible) derived from categories of likelihoods used by the International Panel on Climate Change (Table 3, Mastrandrea et al. 2010), instead of specifying a single probability. We distinguish *the probability of all* CUs being above Red from *the proportion of* CUs above Red (identified as 100% in Step 4). Both CU status-based and aggregate abundance LRPs are set at levels where all CUs are above Red status, but aggregate abundance LRPs assign a probability to this occurrence.

Although DFO's Precautionary Approach Framework (2009) states that LRPs under the Fish Stocks provisions be identified by Science, we were unable to identify a specific probability level for all CUs being above Red status that aligned with scientific principles. Although it may be possible to select a probability level based on the IPCC likelihood categorization scheme (e.g., more likely than not, likely, very likely, virtually certain) further guidance on choosing among these options is required.

### Choose among aggregate abundance LRPs

Guidelines for choosing among two types of aggregate abundance LRPs are described here: logistic regression LRPs and projection LRPs. These methods use either historical or projected data, respectively to identify the relationship between aggregate abundances and the probability that all CUs are above Red status. The guidelines presented at this step are based on the separate assumptions required for each method. If assumptions are not met for either method, then developing aggregate abundance LRPs that are aligned with the WSP may not be possible for the SMU.

Both methods rely on an assumption of positive covariation in population dynamics among component CUs. If this assumption is met, then when one CU has depleted status and contributes relatively few spawners to the aggregate, it is likely that other component CUs will also have depleted status contributing few spawners to the aggregate. Similarly, if one CU is considered healthy and contributes many spawners, other CUs are more likely to be healthy.

Given the range of uncertainties and limitations associated with each method, the application and comparison of both methods may be prudent instead of limiting analyses to a single approach (see Step 9).

### Logistic Regression LRPs

Empirical logistic regression LRPs are derived from historical time-series of the proportion of CUs above Red status, indicated by a single metric on spawner abundances or distribution.

LRPs based on logistic regressions may be appropriate when the following assumptions are met:

- CU assessments are derived primarily from abundances relative to benchmarks or distribution of spawners instead of time trends, or status on spawner abundances relative to benchmarks are considered a suitable approximation. It is possible to combine two or more types of abundance-based benchmarks to assess CUs within an SMU (e.g., use both percentile and $S_{gen}$ benchmarks to assess different CUs).
- As required for CU status-based LRPs, data-deficient CUs meet criteria outlined in Step 3 such that their status can be represented by CUs with data.
- Time-series of the proportion of CUs above the lower benchmark contain contrast such that all CUs are above their lower benchmark in at least one year and at least one CU is below its lower benchmark in at least one year.
- There is a statistically significant positive relationship between aggregate abundances and log-odds of all component CUs being above their lower benchmark without influential outliers, as supported by model diagnostics described in Holt et al. (2023). This relationship

tends to be significant and positive when pairwise correlations in spawner abundances among CUs are strong and positive. For example, for our case study on Interior Fraser Coho, goodness-of-fit diagnostics identified a significant relationship between aggregate abundances and log-odds of all component CUs being above their lower benchmarks ($p<0.01$) and the average pairwise spawner correlations among CUs was relatively high, 0.56. In contrast, for our case study on Inside South Coast Chum, *Oncorhynchus keta*, the same goodness-of-fit diagnostic was not statistically significant ($p=0.13$) and average pairwise spawner correlations was relatively weak, 0.12.

- Residuals for logistic regression model fit are independent (i.e., not temporally autocorrelated).
- Environmental drivers and threats among CUs have remained stable over the available time-series, or have changed in the same way across CUs such that covariance in population dynamics among CUs is likely to have remained stable over time. As a result, the relationship between aggregate abundances and log-odds of all CUs being above lower benchmarks is also likely to have remained stable.
- CU-level population dynamics are not undergoing directional changes resulting in declines or increases in population dynamic parameters and associated benchmarks.

In preliminary analyses for the Interior Fraser Coho case study, we considered CU status based on multidimensional status from the Salmon Scanner, but have chosen to focus on the single metric approach for several reasons. First, the Salmon Scanner includes status on smoothed abundance data (running generational geometric mean) relative to abundance-based benchmarks, and therefore the status in one year depends on the status in the previous year. Autocorrelation violates the assumption of independence of observations required in the logistic regression. Although logistic regressions can be revised to account for autocorrelated residuals, when autocorrelation is detected the available degrees of freedom are often insufficient given the relatively short time-series of CU assessments. In addition, the Salmon Scanner includes metrics on short- and long-term trends in spawner abundances which are less directly related to, and may be completely unrelated to, aggregate abundances. For CUs that rely on time trends for status assessments, aggregate abundance-based metrics are likely not appropriate (see below).

LRPs based on logistic regressions may not be appropriate when:

- CU assessments are derived from trends in spawner abundances over time (e.g., as part of the Salmon Scanner), and not abundance-based benchmarks.
- Data-deficient CUs do not meet criteria outlined in Step 3 such that their status cannot be represented by CUs with data.
- Time-series of the proportion of CUs above their lower benchmarks lack contrast (i.e., are equal to 100% for all years, or less than 100% for all years).
- The relationship between aggregate abundances and log-odds of all component CUs being above their lower benchmark is not statistically significant or contains influential outliers. In other words, model diagnostics do not support the use of logistic regression.
- Residuals for logistic regression model fit are temporally autocorrelated such that status in one year depends on the status in the previous year.
- Threats and/or environmental drivers have changed such that CU-level benchmarks estimated from historical data are no longer meaningful, and there is no expectation that these changes will revert naturally to their preexisting state, or be achievable through management. Or,

environmental drivers and threats among CUs have changed over the available time-series such that covariance in population dynamics among CUs is likely to have changed.

- There is only one CU in the SMU. In this case, the CU-level status represents the SMU-level status.

**Projection LRPs**

Projection LRPs are derived from projections of CU-level population dynamics and associated time-series of CUs above Red status as indicated by a single metric, spawner abundances relative to a lower benchmark. CU status derived from multidimensional assessments within the Salmon Scanner were not considered for projection LRPs because the projection model identifies long-term equilibrium aggregate abundances associated with specified probabilities of component CUs being above lower benchmarks and is not structured to reflect time trends. Time trends can be assessed in simulation models that evaluate the impacts of management procedures on population dynamics from current status, as in MSEs.

Projection LRPs may be appropriate when:

- CU-specific stock assessment models have been developed including parameterization of spawner-recruitment models and the covariance in recruitment residuals among CUs. These models and their parameters account for hatchery contributions when populations are influenced by hatcheries, are peer reviewed, and represent current dynamics of natural spawners and recruitment.
- Where peer-reviewed population dynamics parameters are not available or are no longer current, plausible bounds can be placed on uncertain parameters (e.g., productivity and capacity), including those that may have changed over the time-series to represent a best-estimate of current conditions. These bounds can be derived from neighbouring CUs, meta-analyses, or expert opinion.
- These CU-specific parameters are available for representative CUs within the SMU (as identified in step 3)

Projection LRPs may be inappropriate when:

- Population dynamics parameters cannot be estimated, and/or plausible ranges are not known.
- Projection LRPs are used to evaluate status under a new management procedure that is not considered in the projection model. Projection LRPs depend on the specific management procedure applied in the projections, implemented as a constant exploitation strategy for our case studies. However, sensitivity analyses of projection LRPs to various exploitation rates or management procedures can demonstrate aggregate abundances required to maintain CUs above their lower benchmarks under a variety of possible management scenarios, and the sensitivity of management choice to the aggregate abundance LRP.
- There is only one CU in the SMU. In this case, the CU-level status equates to the SMU-level status.

Furthermore, projection LRPs may be more appropriate when pairwise correlations in spawner abundances among CUs are positive and strong, but this is not a requirement. It is possible to estimate projection LRPs for an SMU with component CUs that vary independently. However, when correlations between CUs are low, the aggregate abundance LRP will be high because there is a higher probability of any one CU having Red status. In these cases, CU status-based LRPs and harvest control rules that manage CUs independently may be more appropriate. Although higher LRPs under asynchronous dynamics may initially be counter-intuitive due to the stability asynchrony provides to aggregate time-series (Schindler et al. 2010), independent trajectories among components increases risks of individual component CUs dropping below lower benchmarks in mixed-CU fisheries necessitating higher LRPs.

Model evaluation for projection LRPs is more subjective than for logistic regression LRPs. The suitability of logistic regression model fits can be evaluated using statistical model fit diagnostics, which makes the evaluation process relatively objective and repeatable. However, the added assumptions and analytical decisions required to parameterize projection models is a more subjective process in which outcomes may vary among analysts. Peer review, as described in step 6 above, will be required to support the development of projection LRPs.

#### 5.1.9. Step 9: Apply aggregate abundance LRPs to derive SMU-level status and compare to status against CU status-based LRPs

Aggregate abundance methods are then applied to derive LRPs based on the guidance above. See Appendix A and Holt et al. (2023) for example applications. When status of an SMU is inferred from aggregate abundance LRPs using a subset of CUs that are considered representative of the remaining data-deficient CUs, then the resulting status should be considered ‘provisional’ (i.e., with increased uncertainty) until the status of all component CUs can be assessed. When status of data-deficient CUs cannot be inferred from data-rich CUs, status cannot be assessed with aggregate abundance LRPs.

We use generational mean spawner abundances as a basis for determining whether the SMU is above or below its LRP. A generational mean integrates status over cohorts within a generation, which are generally independent of each other because of the anadromous, semelparous life-history of Pacific salmon and the dominance of a single age-at-maturity for many stocks (Holt et al. 2009; Porszt et al. 2012). As a result, generational smoothing reduces noise in annual CU status determination arising from both interannual variability in CU abundances from different cohorts and annual observation error in estimated spawner abundances. It also makes our determination of LRP status consistent with the approach taken for abundance-based benchmarks in published WSP assessments (e.g., Grant et al. 2020a) and the Salmon Scanner at the CU level. Further, we recommend that SMU status be evaluated approximately every salmon generation to align with guidance for generational CU assessments under the WSP (Grant and Pestal 2013; Grant et al. 2020a).

**Compare Aggregate Abundance LRPs**

Using multiple analytical approaches to define LRPs is consistent with the principle of using the best available information if evidence to support one method over the other is lacking. Statuses that converge among methods provide a stronger weight-of-evidence that the chosen LRP represents a level above where serious harm may occur. Although LRPs that converge may be based on assumptions that are coincidentally incorrect, the principle of Occam’s razor supports explanations with fewer exceptions. When LRPs diverge, the underlying assumptions causing those divergences should be explored and further reviewed.

**Compare Status from Aggregate Abundance LRPs to that from CU status-based LRPs**

In this step, we recommend comparing status from aggregate abundance LRPs to that obtained from CU status-based LRPs identified in Step 5. While aggregate abundance LRPs exploit observed covariation in population dynamics among component CUs, several factors can lead to a break-down in that relationship (e.g., observation errors, temporal variation in covariation, and/or infrequent extreme events). Hence, statuses from aggregate abundance LRPs may differ from those based on CU status-based LRPs. We recommend CU status-based LRPs as the default LRP to implement the Fish Stocks provisions, with aggregate abundance LRPs supplemental where required for harvest management purposes.

# 6. DISCUSSION

## 6.1. KEY UNCERTAINTIES THAT AFFECT LRP ESTIMATES

**KEY POINTS:**

- Uncertainties in **CU-level benchmarks** affect both CU status-based and aggregate abundance LRPs, and can arise because of:
  - observation errors in underlying data, e.g., related to uncertainty in the hatchery contribution to spawning,
  - estimation uncertainty in benchmarks arising from statistical model fitting and time-varying parameters, and
  - structural uncertainties in model forms.
- Uncertainties can also arise in **CU statuses** due to the choice of metrics used (single or multidimensional). For both aggregate abundance LRPs, uncertainties can arise because CU-level status is based on only a single metric as a proxy for status on multiple dimensions.
- The distribution of spawning among populations within a CU can be important for the viability of the CU and SMU, and ignoring or misidentifying this stock structure may increase uncertainty in assessed status.
- Uncertainties in all the candidate LRPs can arise from the exclusion of data-limited CUs from analyses when these CUs are poorly represented by the data-rich CUs that are included. We recommend caution when applying LRPs that do not include all CUs.
- Uncertainties in **logistic regression LRPs** arise from statistical estimation of the stock-recruitment and logistic regression models, as well as changes in population parameters and covariance among CUs over time.
- Uncertainties in **projection LRPs** can arise from mis-specifying models used in the projections.
- For projection LRPs, uncertainties in underlying parameters and CU-level benchmarks are integrated into the probability of all CUs being above their lower benchmarks, and the LRP itself does not have statistical estimation uncertainty. Projection LRPs explicitly account for underlying uncertainties in population parameters, such as CU-level productivity and capacity, age-structure, covariance in recruitment deviations, and variability in implementation of exploitation strategies over time and among CUs.

#### 6.1.1. CU assessments

Uncertainties in CU-level benchmarks affect both CU status-based and aggregate abundance LRPs, and arise because of observation errors in underlying data, estimation uncertainty in benchmarks, and structural uncertainties in model forms. Each of these three sources of uncertainty in benchmarks are described here.

First, data uncertainties can arise from observation errors in spawner abundances, the proportion of hatchery-origin spawners, catches, stock assignment of catches, and age-at-maturity. These uncertainties impact estimates of recruitment in 'run reconstructions' and assessment of status.

In particular, the impact of hatcheries on spawner and recruitment time-series is a key uncertainty due to the low rates of marking hatchery salmon and sampling on the spawning grounds. Even when data on the proportion of hatchery-origin fish are available and abundance time-series are adjusted to account for these (as in the Interior Fraser River Coho case study), the genetic impacts of hatcheries can perpetuate over multiple generations (Araki et al. 2009; Christie et al. 2014), and are difficult to quantify because second generation hatchery-origin fish are not marked or monitored. This is a source of uncertainty for populations impacted by within-basin (or within-population) hatchery facilities as well as those impacted by straying out-of-basin. Targeted marking and monitoring of spawning grounds for mark proportions and genetic analyses to identify genetic introgression from strays would help address these uncertainties. Further, for populations that are not dominated by hatchery production, the decision to exclude the contribution of hatchery-origin fish from time-series of spawner abundances where possible assumes that these fish do not contribute to assessment and resulting management of wild salmon, as in previous WSP assessments (e.g., DFO 2015), despite their possible contribution to conservation and rebuilding objectives, and ecosystem services in general. A review and evaluation of objectives for integrated-transition and integrated-wild populations (with PNI $\geqslant 0.5$), and the appropriate data on which to base assessments was beyond the scope of this project.

Second, in the estimation of benchmarks, statistical uncertainties can be represented with 95% confidence intervals derived analytically or with bootstrapping (or 95% credible intervals for Bayesian analyses). Short time-series or those with insufficient contrast in spawner abundances can increase estimation uncertainties in benchmarks. For stock-recruitment based benchmarks in particular, observation errors in spawner abundances can bias benchmark estimates ('errors-in-variables'), as can correlations that occur when the spawner abundance in a given year depends on recruitment in the previous generation (time-series biases, Walters and Martell 2004). Uncertainties in percentile-based benchmarks can arise because of uncertainties in productivity and harvest rates required to categorize populations for benchmark identification (as described in Holt et al. 2018). Uncertainties in benchmarks derived from the watershed-area model (Parken et al. 2006; Liermann et al. 2010) may arise due to its parameterization based on spawner-recruit data sets that are outdated (ending in 2000) and likely more productive compared with populations used in our case study. To address this last source of uncertainty, we derived productivity estimates and uncertainties from a life-stage specific model for WCVI Chinook combined with expert opinion. All of these benchmarks may be biased when underlying population parameters change over time and these changes are not reflected in the estimation procedure (see Section 6.3 for more details).

Third, structural uncertainty in stock-recruitment models underlying benchmark estimation can swamp other sources of uncertainty, and requires careful consideration based on available data and biological understanding of the population dynamics, ideally with peer review. We provide one example of structural uncertainty in the Interior Fraser River Coho study based on prior assumptions about population capacity, but other components, such as decisions about depensation at low abundances, shared or independent variability in productivity among CUs, and strength of over-compensation (e.g., Ricker versus Beverton-Holt) should be considered.

In addition to uncertainties in benchmarks, uncertainties can arise in estimated CU statuses due to assumptions made during status assessment. Uncertainty in status can result from the choice of metrics used (single or multidimensional). In some cases, status is best represented by a composite of multiple metrics resulting in uncertainties in status when only a single metric (e.g., spawner abundances) is applied. Furthermore, the distribution of spawning among populations within a CU can be important for the viability of the aggregate, and ignoring or misidentifying this stock structure may result in higher uncertainty in assessed status. Uncertainties can also arise from applying stock-recruitment based benchmarks to spatial scales that are larger or smaller than the scale at which density dependence occurs.

Uncertainties in peer-reviewed WSP assessments are captured qualitatively, as documented in narratives associated with each CU assessment (e.g., DFO 2015). These qualitative estimates of uncertainty are derived from experts who integrate uncertainties in data and benchmarks and often reconcile conflicting metrics. This process requires careful consideration of expertise included to ensure that best available information is incorporated in assessments and associated description of uncertainties. Although uncertainties in CU status derived from the Salmon Scanner are not currently provided, this functionality is being considered for future iterations of the tool. The Salmon Scanner will be applied annually within an expert-driven process led by DFO's State of the Salmon Program, so underlying uncertainties are considered and outputs are verified. A full review of the Salmon Scanner including uncertainties is forthcoming (Pestal et al. In prep.).

#### 6.1.2. CU status-based LRPs

Uncertainties in status derived from CU status-based LRPs can arise from the exclusion of data-limited CUs from analyses when these CUs are poorly represented by the data-rich CUs that are included. To clearly communicate this uncertainty, we suggest labeling these LRPs as provisional when all the data-rich CUs have status above Red. Even when data-limited CUs have similar threats, environmental conditions and drivers, life-history characteristics and capacities as the data-rich CUs, population dynamics may diverge due to other processes that are not accounted for. We recommend caution when applying provisional LRPs that do not include direct information from all CUs. In these cases, we recommend implementing a monitoring program to inform CU-specific assessments.

#### 6.1.3. Aggregate Abundance LRPs

**Logistic regression LRPs**

For logistic regression LRPs, uncertainties can arise from statistical estimation of the stock-recruitment and logistic models. In our case studies, we provide 95% CIs and assess their overlap with current status. These CIs represent uncertainty in the estimation of the logistic regression incorporating uncertainty in the underlying benchmarks (e.g., from spawner-recruitment relationships or the watershed-area model). This occurs because the estimation of the logistic regression model was statistically integrated with the estimation of the underlying spawner-recruitment based benchmarks. This statistical integration allows uncertainties to be propagated from CU-level benchmarks to SMU-level LRPs. When estimated in a Bayesian framework, the probability distribution of LRPs can be generated to provide the probability that the current status is above the LRP given uncertainties in the LRP. In future analyses, uncertainty in current spawner abundances could be integrated with uncertainty to derive probabilities of breaching LRPs that accounts for both sources.

Similar to CU status-based LRPs, uncertainties in logistic regression LRPs can arise from the exclusion of data-limited CUs from analyses when these CUs are not well represented by the data-rich CUs that are included. Further uncertainties in logistic regression LRPs can arise if the management system has changed over time such that selectivity from fisheries among CUs has diverged, or if the covariance in population dynamics has changed due to natural or other anthropogenic factors. In some cases, covariance among CUs may be driven by synchronous trends in hatchery enhancement creating misleading and possibly biased LRP estimates.

Furthermore, uncertainties in both aggregate abundance LRPs (logistic regression and projection LRPs) can arise because these LRPs are derived from CU statuses on a single metric as a proxy for status on multiple dimensions. In some cases, these statuses may diverge because of additional metrics considered and the generationally smoothed time-series used to assess current status in the multidimensional approach (as implemented by the Salmon Scanner).

#### Projection LRPs

Projection LRPs explicitly account for underlying uncertainties in population and harvest parameters, such as CU-level productivity and capacity, age-structure, covariance in recruitment deviations, and variability in implementation of exploitation strategies over time and among CUs. The inclusion of structural uncertainty in the form of different stock-recruitment relationships is demonstrated for the case study on Interior Fraser Coho. We recommend a thorough review of assumptions and either including them directly in random sampling in projections or including them as sensitivity analyses.

One caveat of this approach is that the LRP depends on the management procedure applied in the projections, implemented as a constant exploitation strategy for our case studies. Although management procedures for Pacific salmon often include escapement goals, fixed exploitation limits, and/or a fixed set of exploitation rates that vary with abundances, we have assumed that these procedures can be roughly approximated with a constant exploitation rate with implementation error. Other more realistic management procedures could be considered in future iterations. Projection LRPs derived in this way cannot be used to assess status when management procedures change over time and those changes have not been evaluated in projection.

One difference between projection and logistic regression LRPs is that for projection LRPs, uncertainties in all underlying parameters and CU-level benchmarks are integrated into the probability of all CUs being above their lower benchmarks, so that the LRP itself does not have statistical uncertainty associated with it. In contrast, 95% CIs associated with logistic regression LRPs account for estimation uncertainty not included in projection LRPs.

When considering both logistic regression and projection LRPs under alternative model assumptions, such as different formulation of the stock-recruitment model, LRPs can be chosen based on strength of evidence for underlying assumptions or averaged when alternative assumptions are all equally plausible. Care should be taken when there is little or no overlap in the distribution of LRPs under various model assumptions, where averaging can obscure different plausible realities that would require alternative management actions.

## 6.2. IMPACT OF MISSING CUS ON SMU-LEVEL STATUS

**KEY POINTS:**

- For **CU status-based LRPs** when an SMU contains data-deficient CUs and the remaining data-rich CUs are above Red Status, we recommend SMU status be either provisional (i.e., status with higher uncertainty) or data deficient.
  - SMU status is provisional when data-rich CUs are deemed representative of data-deficient CUs
  - SMU status is data-deficient when data-rich CUs are not representative of data-deficient CUs
- Also for CU status-based LRPs, when any component CU has Red status, we recommend SMU status be assessed as below the LRP regardless of the presence of data-deficient CUs and whether the status data-deficient CUs can be inferred from data-rich CUs.
- For **aggregate abundance LRPs**, we recommend that SMU status be provisional when SMUs contain data-deficient CUs that can be inferred from data-rich CUs, regardless of the status of the data-rich CUs.

For CU status-based LRPs, we recommend SMU status be either provisional (i.e., status with higher uncertainty) or data deficient when an SMU contains data-deficient CUs and the remaining data-rich CUs are above Red Status. This recommendation is based on the potential for positive biases in status based on the data-rich CUs alone. Provisional status can be assigned to SMUs where the data-rich CUs are representative of data-deficient CUs (reflecting high uncertainty in status), and data-deficient SMU status can be assigned where the data-rich CUs are not representative (Table 5). The power to detect a breach of a CU status-based LRP is relatively weak when the sample size of the data-rich CUs is small relative to the total number of component CUs. Therefore, statuses that rely on only a small number of CUs within an SMU tend to provide more optimistic status than those that include a larger sample of CUs for CU status-based LRPs, as shown for Inside South Coast Chum case study.

In contrast, if the LRP of 100% of CUs above Red status has been breached for an SMU with data-deficient CUs, the inclusion of additional CUs may further deplete or improve status defined as the percentage of CUs above Red status, but will not change the fact that the LRP has been breached. This asymmetrical impact of increased monitoring of CUs on SMU status may reduce incentives to extend monitoring to data-deficient CUs.

For aggregate abundance LRPs we recommend that SMU status be provisional when SMUs contain data-deficient CUs that can be represented by data-rich CUs regardless of the status of the data-rich CUs. For these LRPs, we found that removing component CUs from assessment of an SMU tended to increase variability in SMU-level status, which may be more pessimistic or optimistic than when all CUs are considered depending on which CU is removed and the level of covariation among CUs. For logistic regression LRPs in particular, the removal of CUs affects the fit of the logistic regression model, which impacts estimated status relative to LRPs in ways that are difficult to predict *a priori*, as shown for the Interior Fraser Coho case study. In addition, for aggregate abundance LRPs we recommend data-deficient status for SMUs with component data-deficient CUs that cannot be inferred from the data-rich CUs.

## 6.3. FUTURE RESEARCH

**KEY POINTS:**

- We recommend future research be prioritized to evaluate the impacts of:
  - Temporal trends in underlying population processes such as intrinsic productivity and carrying capacity on biological benchmarks and reference points.
  - Adapting LRPs to include a broader scope for serious harm, including ecosystem and habitat considerations, the distribution of spawning within CUs, and Indigenous Knowledge.
  - Simulation evaluation of LRP methods given temporal variability in population parameters and other sources of uncertainty.

We recommend future research on the impacts of time-varying parameters, adapting LRPs to include a broader scope for serious harm, and the evaluation of LRP methods, as described in more detail below. We highlight time-varying parameters due to their pervasiveness in Pacific salmon population dynamics and documented impacts on reference points.

### 6.3.1. Time-varying parameters and impacts on LRPs

There is increasing evidence of time-varying population processes in Pacific salmon populations, particularly relating to trends in productivity (Peterman and Dorner 2012; Malick and Cox 2016; Dorner et al. 2018). In Canada, DFO assessments have identified declines in productivity for various CUs, e.g., Fraser River Sockeye (Grant et al. 2012; Grant and Pestal 2013; Huang et al. 2021), Southern BC Chinook (DFO 2016b), and Interior Fraser River Coho (Arbeider et al. 2020). These assessments relied on a variety of tools to identify trends in productivity including the evaluation of trends in recruits per spawner (Arbeider et al. 2020) and residuals from recruitment curve fits (Grant et al. 2012), and explicit consideration of time-varying parameters when fitting recruitment curves using Kalman filter or recursive Bayes approaches (Huang et al. 2021). However, determining support for time-varying parameters is not always straightforward. Common statistical diagnosis such as inspection of residuals and use of information criteria (e.g., AIC and BIC) often produce conflicting results (Holt and Michielsens 2020). Evidence for changes in capacity over time are encountered less often in Pacific salmon populations, but the potential impacts of time-varying capacity have been explored in simulation studies and may be important, although it is usually less impactful than changes in productivity (Holt 2010; Dorner et al. 2013). Changes in population demographics, such as size at age and age-at-maturity are also known to influence population dynamics and reference points. Failure to track interannual changes in age-at-maturity can lead to biased stock-recruitment parameter estimates and underestimation of model variance (Bradford 1991; Zabel and Levin 2002).

Time-varying recruitment parameters and population demographics affect estimates of salmon benchmarks, e.g., $S_{MSY}$ and $S_{gen}$ (Holt and Michielsens 2020; Staton et al. 2021) and are also likely to affect population trends, resulting in changes to benchmarks based on historical observations (e.g., percentile-based benchmarks, Holt et al. 2018). Analytical methods for time-varying reference points have been proposed for other marine fish species (A'mar et al. 2009; Punt et al. 2014), some of which have been evaluated empirically and in simulation with mixed results (Berger 2019; O'Leary et al. 2020). Berger (2019) suggests that dynamic reference points that track changes in underlying population processes are most useful in situations when stock productivity shifts directionally and the productivity signal is correctly ascertained. In contrast, uncertainty from incorrectly identifying productivity trends can be a major source of inaccuracy in stock status (Berger 2019).

Although evidence for time-varying population processes is strong, guidance on incorporating these changes into assessment and management of Pacific salmon are lacking. In a review of stock-recruitment analyses for Pacific salmon, Adkison (2021) highlighted that even when there is strong evidence for non-stationarity in population dynamics it is not clear if reference points should be adjusted accordingly. Where stock depletion is associated with time-varying parameters that are thought to be reversible, it may be more appropriate to protect the population from harvest by maintaining reference points using all historical data (DFO 2013; Szuwalski and Hollowed 2016). DFO (2006) recommended that changes to reference points should only occur when there is considerable evidence that productivity has changed and there are no expectations that these changes will be reverted naturally or achieved through management. Furthermore, DFO's Precautionary Approach Framework states that "when developing reference points efforts should be made to take into consideration the range of factors which may affect the productivity of the stock including changes in ocean conditions, where information is available"(DFO 2009a). This information can help identify if reductions in productivity are likely to be reversible or only slowly reversible. Klaer et al. (2015) devised a framework for evaluating the degree of confidence in productivity shifts in Australian fisheries, and similar approaches could be adapted for Canadian salmon populations.

Even if time-varying benchmarks or reference points are considered, it is difficult to define how often they should be changed (Zhang et al. 2021a). Mistimed changes in benchmarks or reference points may lead to biases in stock status and volatility of management responses may lead to management uncertainty, reducing trust in the management process (Adkison 2021). Recent studies recommend the use of case-specific feedback simulation exercises in order to determine the appropriate scale to adjust reference points when stock-recruitment parameters are non-stationary (Holt and Michielsens 2020; O'Leary et al. 2020; Zhang et al. 2021b). However, full feedback simulation studies might not be feasible for every CU where trends are suspected due to limited resources.

Further research identifying when and how to account for time-varying parameters and demographics in assessments and management of Pacific salmon is warranted, and is currently underway within DFO. Current WSP assessment methods do not consistently account for time-varying dynamics and their impacts on status and the resulting LRP estimates. Guidance on accounting for time-varying parameters that differ among CUs within an SMU is also warranted. Time-varying stock-recruitment dynamics usually occur at the CU level, and the implications for SMU-based LRPs that contain multiple CUs are not straightforward. There are no clear guidelines on how to translate time-varying stock-recruitment parameters for CUs into aggregate-level LRPs. Effects of time-varying CU recruitment dynamics on aggregate abundance and CU status-based LRPs will depend on the degree of synchrony among CUs, the direction of the change in recruitment parameters, and past and current stock status, among other factors. For example, in our case study on Interior Fraser River Coho Salmon, when a consistently lower productivity level was introduced through an alternative stock-recruitment model formulation (one that included informative priors on capacity in CU-level spawner-recruitment models), benchmarks increased for most CUs as did the aggregate abundance-based LRP for the SMU. However, in cases where productivity varies at different rates among CUs or capacity changes as well, impacts on CU-level benchmarks and SMU-level LRPs will not be easily predictable.

### 6.3.2. Adapting LRPs to include a broader scope of serious harm

We recommend future research into LRPs that consider the ecosystem component of serious harm for Pacific salmon and include longer time frames for assessing thresholds of serious harm. The ecosystem component of serious harm could be considered by accounting for the importance of Pacific salmon populations for marine ecosystems (Nelson et al. 2019; Walters et al. 2020; Trochta and Branch 2021) and the impacts of salmon migration on the inflow of marine-derived nutrients into freshwater and estuarine ecosystems (Schindler et al. 2003; Hocking and Reimchen 2006; Field and Reynolds 2011; Quinn et al. 2018). While the definition of serious harm under DFO's Precautionary Approach Framework encompasses impacts to the ecosystem, associated species and a long-term loss of fishing opportunities (DFO 2009a), the assessment of harm to these components depends to some extent on the time frame being considered. Assessments that include only very recent data may miss large declines in status and ecosystem impacts that occurred historically before the advent of modern survey records. In some cases, considering a longer view from genetic, archeological, palaeoecological, or Indigenous Knowledge has demonstrated that recent declines are part of much larger historical declines associated with large-scale ecosystem impacts (McKechnie et al. 2014; Eckert et al. 2018; Lee et al. 2019; Price et al. 2019).

Indigenous Knowledge has been considered in the development of target reference points for fisheries management (Caddy and Mahon 1995), and there is value in further considering its role in identifying serious harm. Reid et al. (2021) introduce the concept of Two-Eyed Seeing (Etuaptmumk in Mi'kmaw), where both Indigenous and Western science perspectives are valued through the process of, "learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together, for the benefit of all". By investigating serious harm, reference points, and the time-varying nature of these concepts from both Indigenous and Western scientific perspectives, LRPs may better reflect biological processes underlying both knowledge systems. This step requires engagement and collaborate with Indigenous Peoples to co-lead and co-produce research on pairing Indigenous Knowledge with Western science-based LRPs.

In addition, the distribution of spawning within CUs is a component of CU assessments under the WSP, but robust metrics and benchmarks of distribution are lacking. Future research on assessment methods that more rigorously considering population structure within CUs would benefit both CU assessments under the WSP and assessments relevant to First Nations who often rely on salmon populations at relatively fine spatial scales.

Alternative LRP methods may be developed in the future to capture a broader range of data availability, quality, and types, and dimensions of biological status, aligned with the key principles in Section 3. As methods are developed and revised, SMU statuses can also be updated in accordance with Principle 1, using the best available information for the development of LRPs.

### 6.3.3. Evaluation of LRP methods

We recommend further consideration and evaluation of the four proposed criteria to identify if data-limited CUs can be inferred by data-rich CUs (Step 3, Section 5). For example, these criteria (and/or other considerations) could be applied to SMUs where CU statuses are available to assess the extent to which statuses covary when CUs are deemed representative of each other. Simulation evaluation could further evaluate the extent to which CU statuses on a single metric of status covary under a range of plausible underlying covariance structures in recruitment, age-at-maturity, and exploitation rates.

In addition, we recommend simulation evaluation of logistic regression LRPs and projection LRPs to assess impacts of data limitations related to the number of CUs with data and assumptions about population dynamics and covariance among CUs. We recommend that these evaluations be parameterized to the SMUs where their application is proposed to ensure results are relevant to the specific context under consideration.

When applying methods to specific case studies, we recommend that aggregate abundance LRPs consider major structural uncertainties either through sensitivity analyses or model ensemble approaches. These analyses can determine how sensitive aggregate abundance LRPs are to key model uncertainties, including those related to time-varying parameters, depensation at low abundances, observation errors, and covariance in both population dynamics and vulnerability to harvest. We emphasize the critical importance of this step considering a wide range of hypotheses about underlying dynamics. Indeed, standard stock-recruitment models may have limited use if they do not capture the dynamics currently observed. In addition, we recommend simulation evaluation to assess the robustness of LRPs to violating underlying analytical assumptions. Simulation evaluation could further be used to assess the frequency of updates to LRPs required to achieve objectives given underlying changes in model parameters and structure.

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# APPENDIX A. CASE STUDIES

We illustrate the application of the candidate methods for LRPs developed in Section 4 to three SMUs as case studies, evaluate sensitivity of LRPs to various assumptions, and use these applications to inform the guidelines presented in Section 5. The case studies included Interior Fraser River Coho Salmon, West Coast Vancouver Island (WCVI) Chinook Salmon, and Inside South Coast Chum Salmon (excluding Fraser River CUs), each comprised of 3-7 component CUs. These SMUs were chosen because they spanned a wide range of data types and availabilities from data-rich (Interior Fraser River Coho) to data-limited (Inside South Coast Chum). Furthermore, they varied in hatchery contributions from high (WCVI Chinook) to relatively low (Interior Fraser River Coho and Inside South Coast Chum), and two of these case studies are included in the proposed first batch of stocks to be put under regulation for the Fish Stocks provisions (Interior Fraser River Coho and WCVI Chinook). For each case study, the set of LRP methods considered is a function of available data and previously developed assessment methods for component CUs. In this section, we provide a brief description of each case study and methods applied to each. For more complete descriptions of case studies, including SMU characteristics, data sources, analysis methods, and results, see Holt et al. (2023).

## A.1. INTERIOR FRASER RIVER COHO

The Interior Fraser Coho Salmon Stock Management Unit (SMU) includes Coho Salmon that spawn in the Fraser River and tributaries upstream of Hells Gate in the Fraser Canyon. This SMU consists of 5 CUs: Middle Fraser, Fraser Canyon, Lower Thompson, North Thompson, and South Thompson (DFO 2015). Declines in Interior Fraser Coho spawner abundance throughout the 1990's led to a suite of management actions to promote recovery, including significant fishery restrictions starting in 1998 (Decker et al. 2014). Previous work by the Interior Fraser Coho Recovery Team (IFCRT) identified 11 subpopulations nested within the five CUs, and developed recovery objectives based on maintaining abundances of each sub-population above conservation thresholds (Interior Fraser Coho Recovery Team 2006). In 2014, a peer-reviewed WSP status assessment classified three of these CUs as being amber status (Middle Fraser, Fraser Canyon, South Thompson) and the remaining two CUs as amber/green status (Lower Thompson, North Thompson) (DFO 2015). As part of the WSP assessment, $S_{gen}$ was estimated for each CU and used as one of several benchmarks considered when determining integrated CU status.

We used data on total annual spawner abundances, recruitment by age (from natural spawning), and hatchery-based smolt-to-adult survival rate indices covering return years 1998-2020 to derive CU-level spawner-recruitment based benchmarks. Data on natural-origin spawner abundances at each of the 11 sub-populations summed to CU level were used to assess status and trends at the CU level for CU status-based and logistic regression LRPs. These data, along with exploitation rates were used to parameterize the projection model for projection LRPs. Hatchery contribution to production was usually small in this SMU, with PNI values >0.5, and usually >0.72. Spawner abundances are positively correlated among CUs, with an average correlation of 0.56 (Figure A.1). We characterized CU status in three ways, using: (1) the Pacific Salmon Status Scanner, (2) CU-level abundances relative to $S_{gen}$ as a lower benchmark on abundance derived from spawner-recruitment relationship under the WSP, and (3) the distribution of spawning abundance relative to distributional targets developed by the IFCRT (Interior Fraser Coho Recovery Team 2006). In the second approach, we further considered two structural assumptions about the spawner-recruitment relationship based on Korman et al. (2019) and Arbeider et al. (2020), which related

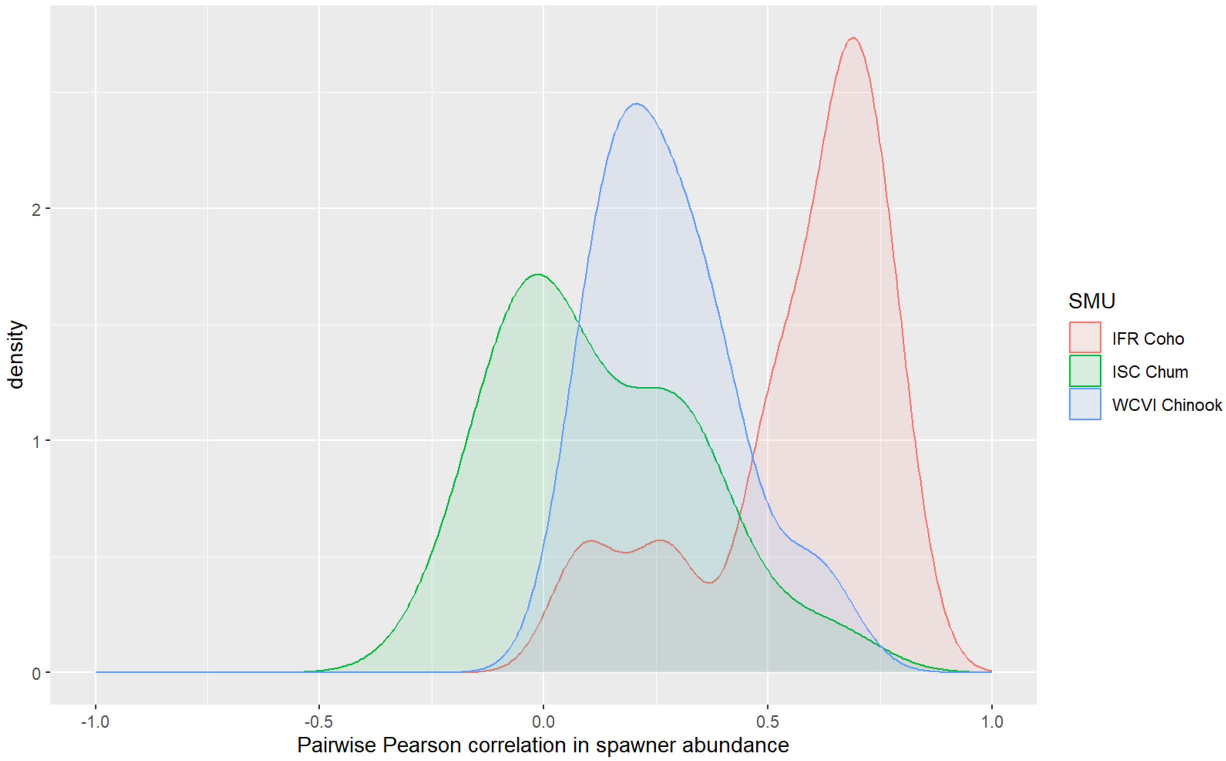


*Figure A.1. Distribution of correlations in spawner abundances among CUs (or inlets for WCVI Chinook) for the three case studies*

to the strength of density dependence. The third approach recognizes that an adequate distribution of spawners across subpopulations may be required for long-term persistence of the SMU (Interior Fraser Coho Recovery Team 2006), and that a contraction of that distribution may represent increased risk of extinction (Arbeider et al. 2020). While multidimensional approaches, such as the Pacific Salmon Status Scanner are recommended for WSP assessments (Holt et al. 2009), we applied the other two approaches (2) and (3) to support the development of aggregate abundance LRPs and for a point of comparison with the Salmon Scanner. Even though aggregate abundance LRPs are not required for harvest management of this SMU, we provide logistic regression and projection LRPs for demonstration purposes. Fisheries on Interior Fraser Coho are managed under a bilateral Canada/US management regime, detailed in Annex IV Chapter 5 of the Pacific Salmon Treaty.

For this SMU, we evaluated the sensitivity of LRPs based on aggregate abundances to data availability with a retrospective analysis by re-estimating CU-level benchmarks, CU statuses, and SMU-level LRPs each year using only the data prior to that year. We also implemented a sensitivity analysis where one or two CUs were removed from the analyses iteratively and CU-level benchmarks, CU statuses, SMU-level LRPs, and SMU-level statuses were re-estimated. We further ran sensitivity analyses related to structural assumptions about the stock-recruitment relationship when deriving CU-level benchmarks for CU status-based and aggregate abundance LRP methods.

We found that LRPs and resulting status were most sensitive to structural assumptions about the shape of the stock-recruitment relationship. LRPs were less sensitive to LRP methods or CU assessment approach (Pacific Salmon Status Scanner versus single-metric on spawner abundances versus single metric on distribution) or the addition of more years or CUs of data. However, we note that for logistic regression LRPs, the exclusion of CUs resulted in larger uncertainties in SMU-level status, though the 95% CIs of status usually overlapped with the status estimated using all the data.

For this case study, we further demonstrated the approach of averaging over structural uncertainties to provide a projection LRP that accounts for that uncertainty. Similar averaging is also possible for logistic regression LRPs.

## A.2. WEST COAST VANCOUVER ISLAND CHINOOK

The WCVI Chinook SMU consists of three CUs (Holtby and Ciruna 2007), seven large inlets (or sounds), and 20 escapement indicator populations distributed across the seven inlets and three CUs. Escapement indicator populations are those with relatively complete time-series of spawner abundances with consistent observation methodology (Riddell et al. 2002; Pacific Salmon Commission Sentinel Stocks Committee 2018). Hatchery enhancement is a substantial component of many of these populations, however, only escapement indicator populations without significant hatchery enhancement (PNI $\geqslant$ 0.5) were included in our analyses (see Section 4). Because time-series of the proportion of hatchery-origin spawners are not available for these populations, total spawner abundances were used in the assessment of CU and aggregate SMU level statuses, which may result in overly optimistic assessments of status relative to analyses excluding hatchery-origin fish (as in the Interior Fraser River Coho case study). Spawner abundances tend to be positively correlated among inlets within the SMU, with an average correlation of 0.28 (Figure A.1).

For WCVI Chinook, inlets nested within CUs are considered an important spatial scale of biodiversity given the geographic separation of spawning habitats among inlets, and limited straying observed among inlets (D. McHugh pers. comm. DFO South Coast Stock Assessment). We therefore considered spawner abundances at the scale of inlets within CUs because of expected limited demographic exchange at this spatial scale.

Two of the three CUs in this SMU, WCVI-South and WCVI-Nootka & Kyuquot, were assessed as Red status in a recent integrated Wild Salmon Policy assessment (DFO 2016b). WCVI Chinook was identified as a stock of concern in the 2021 Integrated Fisheries Management Plan (IFMP) and a rebuilding plan is under development (DFO 2021e). Poor smolt-to-age-2 survival for WCVI Chinook and low spawner levels over the past two decades were highlighted as reasons for conservation concern in the IFMP (DFO 2021e).

Biological benchmarks have been estimated for WCVI indicator populations using an empirical relationship between watershed area and two stock-recruitment biological benchmarks, $S_{REP}$ (spawner abundances at replacement) and $S_{MSY}$, based on a meta-analysis of 25 Chinook stocks across North America (Parken et al. 2006). Lack of rigorous recruitment data for WCVI Chinook stocks precludes the use of stock-recruitment based benchmarks. For the development of LRPs for WCVI Chinook, the empirical relationship between watershed area and $S_{REP}$ was re-estimated using a hierarchical Bayesian model (as in Liermann et al. 2010), and applied to WCVI Chinook inlets.

We characterized CU status in two ways for this case study, using: (1) the Pacific Salmon Status Scanner, (2) CU-level abundances relative to $S_{gen}$ derived from watershed-area model estimates of $S_{REP}$ and productivity derived from a life-stage specific survival model with expert opinion. We calculated two types of LRPs: CU status-based LRPs and projection LRPs. Based on CU-level assessments, there were no years in the historical data where all CUs were above the Red zone, so it was not possible to identify logistic regression LRPs. Even though aggregate abundance LRPs are not required for harvest management of this SMU, we provide projection LRPs for illustrative purposes. Fisheries are managed based on a combination of the bilateral Canada-US management regime specified under the Pacific Salmon Treaty and local co-governance. We implemented sensitivity analyses on projection LRPs across two key uncertainties: variability in exploitation among inlets and intrinsic productivity. Further analyses exploring impacts of exploitation, variability in intrinsic productivity, and capacity are provided in Appendix D of Holt et al. (2023).

We found that status was consistent across the LRP methods that were available, and with a previously published assessment. However, projection LRPs were highly sensitive to underlying population productivities. Although the base-case LRP assumes a relatively diffuse distribution of productivities aligned with the range of expert opinion, reductions (by 25%) or increases (by 50%) in productivities among inlets resulted in relatively large changes in LRPs estimates.

## A.3. INSIDE SOUTH COAST CHUM - NON-FRASER

The Inside South Coast Chum - Non-Fraser SMU (hereafter ISC Chum) includes seven CUs of chum salmon from rivers that drain into Johnstone Strait and the Salish Sea along the mainland of British Columbia and the east coast of Vancouver Island. Chum salmon CUs spawning in the Fraser River watershed are excluded from this SMU as they have been categorized as a separate SMU (Inside South Coast Chum - Fraser). While these two SMUs have substantial overlap in ocean fisheries, they have been separated into two SMUs based on differences in terminal fisheries and freshwater habitats. Godbout et al. (2004) identified variable but stable status in the central and southern portions of this SMU, with declines in the north, especially in the region defined by the Southern Coastal Streams CU component. Holt et al. (2018) found similar results in a provisional WSP assessment of status. Spawner abundances tend to be only very weakly correlated among CUs for this SMU, with an average correlation of 0.12 (Figure A.1).

The ISC Chum SMU is considered data-limited. While escapement time series are available for many streams starting in 1953, several series are incomplete and require infilling assumptions in order to produce a standardized data set over the full length of the time series. The quality of recruitment data is not sufficient to reliably estimate parameters from stock-recruit relationships for use in stock-recruitment benchmarks. Instead, benchmarks were calculated as a percentile of the historical CU-level spawner abundance time series (percentile benchmarks) to inform WSP status, as recommended by Holt et al. (2018). We removed three systems with high levels of enhancement from the Georgia Strait CU (one with large hatchery production and two with extensive artificial spawning channels). The remaining systems had a mix of relatively small hatchery production or no hatchery production (see Lynch et al. 2020). Where available, annual estimates of hatchery-origin spawners were removed from total spawner abundances.

For this case study, we consider two approaches for characterizing CU status: (1) the Pacific Salmon Status Scanner and (2) a single-metric on spawner abundances using percentile-based benchmarks. We applied both the CU status-based LRP and logistic regression LRPs to this case study and evaluated the sensitivity of SMU-level status from CU status-based LRPs to various data inputs. We were not able to generate reliable logistic regression LRPs for this SMU because logistic regression models did not fit the data well, as shown by model diagnostics.

We found that assessments based on the Pacific Salmon Status Scanner gave identical results to the single-metric on spawner abundances relative to percentile-based benchmarks. Also, as for Interior Fraser River Coho, increasing the number of CUs included in analyses always resulted in more pessimistic statuses relative to the LRP.

# APPENDIX B. RESOURCES FOR THE IMPLEMENTATION OF LRPS

- For single metrics of status used under the Wild Salmon Policy, see the Github repository WSP Metrics
- For implementation of CU status-based and aggregate abundance LRPs to three case studies, see the Github repository on case studies
- For estimation of correlations among CUs within SMUs, see the Github repository on CU correlations
- For write-up of this working paper, see the Github repository in csasdown

All data manipulation and projections were performed in R. TMB and TMBStan were used for estimation of stock-recruitment parameters and benchmarks for logistic regression and projection LRPs.

# APPENDIX C. META-ANALYSIS OF CORRELATIONS IN SPAWNER ABUNDANCES AMONG CUS WITHIN SMUS

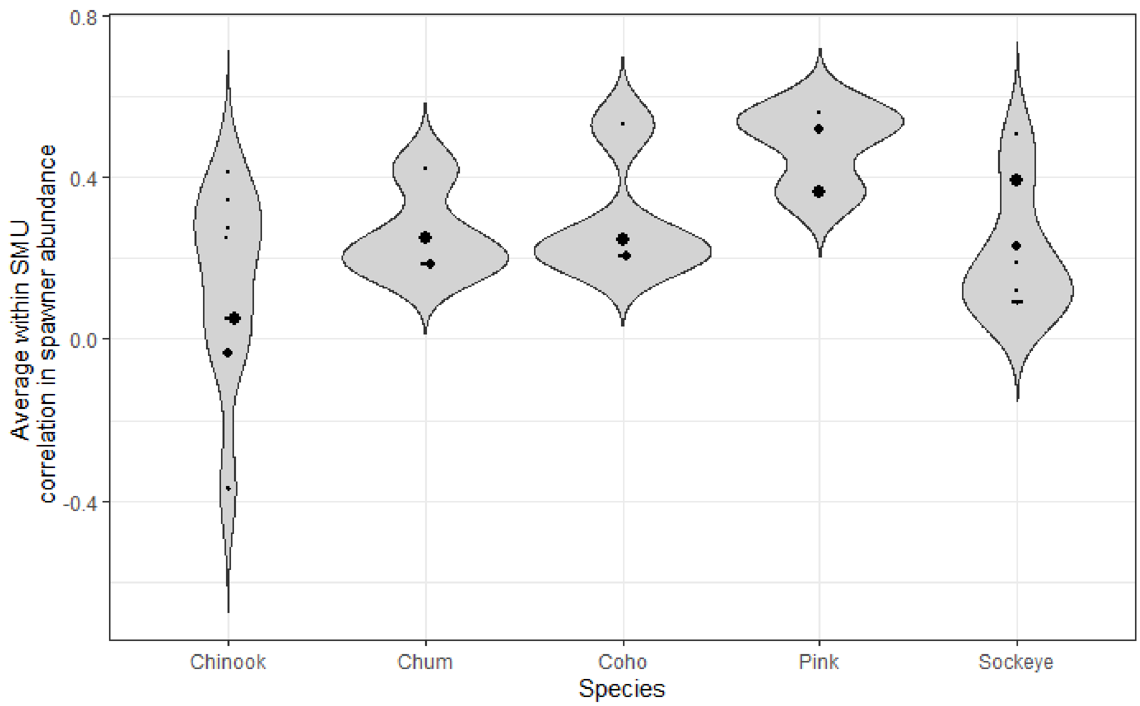


*Figure C.1. Distribution of mean pairwise correlations between CUs for 40 SMUs of Pacific salmon arrange by species. Points are scaled to the number of CUs within a SMU with the largest point equal to 25 CUs.*

In a meta-analysis of spawner time-series across Pacific salmon species throughout BC, pairwise correlations in spawner abundances among CUs within SMUs tended to be positive for Pink, Chum, Coho, and Sockeye Salmon. For Chinook Salmon, correlations were more variable among CUs and sometimes negative, in part due to the confounding influence of hatchery production in some of those systems. A pervasive problem with correlation analyses for Pacific salmon is that populations with available time-series tend to be more heavily managed or suitable for less expensive spawner surveys, and may not represent those without data which tend to be remote, expensive for spawner surveys, and without direct management interventions. Data are taken from the Pacific Salmon Explorer, provided by E. Hertz (Pacific Salmon Foundation, July 2020). A link to the Github repository containing code to perform these analyses are provided in Appendix B.