ISAB

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Columbia River Basin Indian Tribes,
and National Marine Fisheries Service
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Review of the Coast-Wide Analysis of Chinook Salmon Smolt to Adult Returns (SARs) by Welch et al.


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ORIGINAL ARTICLE

A synthesis of the coast-wide decline in survival of West Coast Chinook Salmon (*Oncorhynchus tshawytscha*, Salmonidae)

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Funding information
This study was initially internally funded by Kintama Research Services as part of a separate research effort to assess the credibility of the critical period concept in Pacific salmon. In the course of assembling Strait of Georgia SAR data, we discovered that Chinook survival in many rivers of the Strait of Georgia region had fallen to levels well below those reported for Snake River Chinook. We developed a proposal and obtained funding from the US Dept. of Energy, Bonneville Power Administration, to cover staff time for coast-wide data collation, analysis and writing of this paper (Contract # 75025). The funder (BPA) played no role in the design of the study nor the conclusions reached and was not made privy to the specific contents of this manuscript prior to journal submission.

Abstract
We collated smolt-to-adult return rate (SAR) data for Chinook salmon from all available regions of the Pacific coast of North America to examine the large-scale patterns of salmon survival. For consistency, our analyses primarily used coded wire tag-based (CWT) SAR estimates. Survival collapsed over the past half century by roughly a factor of three to ca. 1% for many regions. Within the Columbia River, the SARs of Snake River populations, often singled out as exemplars of poor survival, are unexceptional and in fact higher than estimates reported from many other regions of the west coast lacking dams. Given the seemingly congruent decline in SARs to similar levels, the notion that contemporary survival is driven primarily by broader oceanic factors rather than local factors should be considered. Ambitious Columbia River rebuilding targets may be unachievable because other regions with nearly pristine freshwater conditions, such as SE Alaska and northern BC, also largely fail to reach these levels. Passive integrated transponder (PIT) tag-based SAR estimates available for Columbia River Basin populations are generally consistent with CWT findings; however, PIT tag-based SARs are not adjusted for harvest which compromises their intended use because harvest rates are large and variable. More attention is needed on how SARs should be quantified and how rebuilding targets are defined. We call for a systematic review by funding agencies to assess consistency and comparability of the SAR data generated and to further assess the implications of survival falling to similar levels in most regions of the west coast.

KEYWORDS
Columbia River, dams, delayed mortality, marine survival, smolt-to-adult return, Snake River

1 | INTRODUCTION

The abundance of salmon (family Salmonidae) in the North Pacific has reached record levels (Irvine et al., 2009; Ruggerone & Irvine, 2018; Schoen et al., 2017); however, most of the increase is in the two lowest valued species (pink, *Oncorhynchus gorbuscha*, and chum, *O. keta*) in far northern regions, at least in part due to ocean ranching (Ruggerone & Irvine, 2018). In contrast, essentially all west coast North American Chinook (*O. tshawytscha*) populations including Alaska are now performing poorly with dramatically reduced productivity (Dorner et al., 2017; Ohlberger et al., 2016).

The situation in North America is similar for most southern populations of coho (*O. kisutch*) (Logerwell et al., 2003; Zimmerman

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Review of the Coast-Wide Analysis of Chinook Salmon Smolt to Adult Returns (SARs) by Welch et al.

Contents

Review of the Coast-Wide Analysis of Chinook Salmon Smolt to Adult Returns (SARs) by Welch et al.

1. Executive Summary

This ISAB report reviews the Welch et al. (2020) paper "A Synthesis of the Coast-wide Decline in Survival of West Coast Chinook Salmon" that examined time series of annual smolt to adult return (SAR) values for many West Coast Chinook salmon populations. The analysis of Welch et al. (2020) highlights the generally low SAR values of Chinook salmon along the coast that have occurred recently, and the paper calls into question the view that Columbia River SARs are anomalously low. Their publication generated debate about the general efficacy of hydrosystem passage and freshwater habitat actions because of some of their broadly stated conclusions. Most importantly, they concluded that changes in freshwater habitat would have little impact on SARs and therefore have only small effects on Chinook salmon populations, a finding which could have major implications for how salmonids are managed in the Columbia River Basin. The ISAB also considered a review of the paper by the Fish Passage Center (FPC 2020) and a response (Welch et al. 2021) to the FPC review.

Some of the descriptive conclusions by Welch et al. (2020), notably the broad geographical distribution of low SAR values for Chinook salmon, are supported by the data and their analyses and also by previous analyses in publications from other research groups. However, their conclusions involving causal inferences, for example about the effectiveness of freshwater habitat initiatives (management actions), are not adequately supported by the evidence. Such conclusions therefore should be considered speculation, especially when interpreted for individual populations. In particular, the degree to which freshwater mortality (i.e., during migration from the point of smolt tagging to ocean entry) influences SAR values varies across populations has not been determined by the Welch et al. (2020) analysis. One cannot directly compare SAR values to infer how freshwater survival differs among populations without making major unsupported and untested assumptions (e.g., assuming marine survival is constant across populations). The ISAB therefore concludes that the Welch et al. (2020) interpretation of the results about the effectiveness of freshwater habitat initiatives for salmon survival are unsupported by the data and evidence they provide and are therefore speculation. Moreover, inferring management implications based on their results alone would be premature.

The Welch et al. (2020) paper adds to other evidence for the need to further investigate SAR values across populations and to continue investigating oceanic and freshwater contributions to low SARs as a critical uncertainty in the basin. The ISAB offers recommendations for further analyses of coastwise SARs related to the treatment of the data for comparability, inclusion of additional explanatory variables, and application of more powerful statistical methods.

Appropriate use of the data

The descriptive analyses and data treatment by Welch et al. (2020) are reasonable for comparing general spatial and temporal trends in SARs from many locations and sources.

However, visual assessment is essentially subjective and can hinder defensible interpretation. Also, changes in tagging and measurement methodology add substantial uncertainty when trends are examined over long timespans with multiple series. In contrast, the subsequent causal interpretations of the analysis of the SAR data by Welch et al. (2020) in terms of the effectiveness of freshwater actions for population-level responses are highly questionable uses of the SAR data. For example, while both coded-wire tag (CWT) and passive integrated transponder (PIT) tag estimates of SARs include a portion of the freshwater phase; these vary by river basin, stock, and tag groups within stocks. CWTs are recovered from adults but do not yield systematic (i.e., site-specific) data on mortality until the salmon recruit to fisheries. In contrast, PIT tags can yield such information on losses during migration (e.g., from one hydroelectric project to another) but are not systematically recovered in fisheries. This major uncertainty, combined with others (e.g., most populations are hatchery-based, lack of statistical rigor, unknown comparability of SAR values among populations) make the conclusions about the effectiveness of freshwater habitat initiatives speculation rather than conclusions supported by the data.

Support of the conclusions

Welch et al. (2020) reach a series of conclusions — some supported by the analysis and some not supported. At a coarse resolution, the descriptive observations of Welch et al. (2020) that SARs for Chinook populations are low in the region and the values for the Columbia system are not dissimilar from those of other systems, including those with no dams, are supported by the analysis presented in the paper. This is useful information and consistent with other analyses previously reported (Kilduff et al. 2014; Dorner et al. 2018).

However, Welch et al. (2020) make additional claims about cause and effect and drew two additional conclusions that the ISAB considers over-interpretation and not supported by their analyses of the SAR data: (1) that there is little evidence of dam-induced delayed mortality, and (2) that there is limited potential for population-level improvement using freshwater habitat restoration. Both conclusions are speculation and not directly supported (or refuted) by the analyses reported in Welch et al. (2020). The reported analyses are poorly suited for detecting the effects of delayed mortality because the analyses did not control for many other influencing factors. Moreover, moving from general patterns and trends in SARs — the interpretation and conclusions about which are supportable — to broader conclusions about the efficacy of freshwater habitat initiatives at specific locations is not supported because the accumulation of issues lead to unacceptably high uncertainty. These issues include: (1) unknown data comparability, (2) inability to accurately isolate the freshwater component of the SARs, (3) lack of statistical rigor in analyses, (4) vagueness in the stated conclusions, and (5) that SARs are primarily from hatchery releases.

Recommendations to improve analyses

The assembly of SAR values in Welch et al. (2020) permits broad analyses of temporal and spatial patterns in SAR values. The ISAB offers several specific recommendations for future analyses into the general temporal and spatial patterns in SAR values. These include:

- Adding explanatory variables to the database, such as age-at-entry, length of river migration, duration of marine residence, and others
- Utilizing a general unified statistical approach that takes full advantage of the pooled cross-section and time-series dimensions of this kind of SARs data
- Limiting claims or inferences about specific populations to those that are supported by robust empirical findings and take advantage of better sources of data when available (e.g., use of PIT tag data for freshwater survival during seaward migration in the Columbia Basin rather than relying on SAR values)
- Distinguishing clearly between observations about levels and trends that can be strongly supported by the analyses versus statements that imply a cause and effect but are not quantitatively supported.

In addition, the ISAB agrees with Welch et al. (2020) that further investigations to better understand survival during the marine phase is warranted.

Fish Passage Center criticisms

The FPC review raises numerous criticisms of Welch et al. (2020) treatment of the data, analyses, and interpretations. The FPC comments are a mix of technical issues, that will not likely have a large effect on the results, and comments that question the interpretations and conclusions made by Welch et al. (2020), who responded to these criticisms in a memo. The ISAB and FPC reviews share concerns about data comparability across populations, lack of statistical methods used, and objection to the overstatement of results and speculative conclusions related to delayed mortality and the effectiveness of actions to improve freshwater phase survival. However, the ISAB does consider that the Welch et al. (2020) analysis, if improved and constrained to interpretations strongly supported by the analysis, can provide a useful large-scale context to the survival of life stages (smolt to returning adults) covered by SAR values for Chinook populations in the region.

Management implications

The ISAB concurs with the general conclusion by Welch et al. (2020) that current SARs for Chinook populations from the Columbia Basin (based on CWT data) and in other systems are generally low, with recent values below 2% (after accounting for fishery interceptions) being common. We also agree that low SAR values from marine survival affect the realization of long-term population-level benefits of freshwater management actions. These findings are useful contributions to the wider literature on Chinook survival patterns and for informing management. However, the effectiveness of habitat improvements to increase adult returns for Columbia Basin Chinook populations (and other individual populations), both historically and into the future, has not been determined by analyses reported in the Welch et al. (2020) paper.

2. Introduction

2a. Review Background

The Independent Scientific Advisory Board (ISAB) was asked by its Administrative Oversight Panel to review the scientific basis for the analysis of regional declines in Chinook salmon survival rates and for the conclusions reported in "A Synthesis of the Coast-wide Decline in Survival of West Coast Chinook Salmon" (Welch et al. 2020). The ISAB conducted this review to provide a technical context for interpreting the findings and the important questions raised by this recent publication and the Fish Passage Center's review of the paper (FPC 2020).

Welch et al. (2020) examine the smolt-to-adult return ratio (SAR) data for multiple populations of Chinook salmon for the Pacific coast to determine whether there are large-scale patterns of SAR values among locations. The assembled SAR values included 123 Chinook salmon populations from southeastern Alaska to central California, with 94 hatchery populations, 26 wild populations, and 3 mixed wild-hatchery populations. Some populations have sub-yearling (i.e., ocean-type) and some yearling (stream-type) life histories. The periods of record vary, and Welch et al. use SAR values estimated from both passive integrated transponder (PIT) and coded wire (CWT) tags. The authors indicate the inherent strengths and weaknesses of the data from each tag type, and they rely primarily on CWT data (rather than PIT data) because CWT are more widespread and incorporate losses in fisheries.

Welch et al. (2020) conclude that Chinook salmon SAR values have declined broadly across the Pacific coast of North America, and that SAR values of 1% or less are widely observed. They note that current SAR values tend to be similar across populations with a wide range of environmental characteristics (e.g., pristine or altered habitats) and ocean entry points. The ISAB notes that while SAR values below 1% (after accounting for fishery interceptions) are common and many populations have recent SARs below 2%, there were also SAR values in the 2-6% range for certain areas and periods of record. In addition, the ISAB notes that Chinook salmon populations in the upper Columbia River and Snake River have SARs that vary geographically, with generally more than half of the years of record having SARs greater than 1% but with many populations and years less than 1% (Coordinated Assessments Indicators of Fish Population Health). In the Interior Columbia River, population replacement (spawning ground adult recruits equal or exceed numbers of original spawners) occurs at SAR values of around 1% or greater, with substantial variation among populations (see Figure 1 below, Chapter 5 in FPC 2017).

The Welch et al. (2020) paper attracted attention because of the broad implications of some of statements in the paper. Some stated conclusions raise questions about the effectiveness and efficiency of management actions to increase adult returns via hatchery releases or improvements in freshwater survival rates. In response to requests from the Oregon Department of Fish and Wildlife and the Washington Department of Fish and Wildlife, the Fish Passage Center conducted a technical review of the Welch et al. paper and raised issues about the paper's methods, results, and interpretations (FPC 2020). Welch provided a written response (Welch et al. 2021) to the FPC review. The FPC review and Welch et al.'s response are considered as part of this ISAB review.

The ISAB conducted this review to provide information and guidance for the Council, NOAA Fisheries, Columbia River Indian Tribes, and other regional policy makers for interpreting the findings of the Welch et al. paper about SARs and implications for management actions. The review also is intended to inform consideration of FPC's criticisms of the Welch et al. (2020) analysis.

2b. Review charge and process

The ISAB's Administrative Oversight Panel asked the ISAB to answer the following five questions:

1. Was the Welch et al. (2020) analysis scientifically sound and were the data it used appropriate for addressing the question?
2. Were the conclusions drawn by Welch et al. (2020) supported by their results?
3. Does the ISAB have recommendations to improve the current analysis and interpretation of SAR values in the future?
4. Are the criticisms raised by the Fish Passage Center supported by the evidence, and do any of those criticisms weaken the Welch et al. (2020) results or conclusions?
5. What are the management implications of the ISAB's conclusions and recommendations?

To answer these questions, our review primarily focuses on Welch et al. (2020). We also consider the comments from the Fish Passage Center (FPC 2020), and subsequent rebuttal (Welch et al. 2021), and other relevant studies and comments, which are cited throughout the text and listed in the Reference section. In addition to these written sources, the authors of the Welch et al. paper presented their analyses to the ISAB in a public forum that included a Question and Answer period with ISAB members. The ISAB appreciates the presentation by Welch et al. and subsequent discussion that occurred during this public forum. The forum was helpful in informing this review. The remainder of this review is organized by the responses of the ISAB to the five review charge questions.

3. ISAB responses to questions

3a. Response to Question 1

Charge question: Was the Welch et al. (2020) analysis scientifically sound and were the data it used appropriate for addressing the question?

The analyses reported in Welch et al. (2020) were exploratory and did not directly address specific hypotheses. However, this approach can provide useful insights. Welch et al. (2020) state their purpose as simply *"… to document broad patterns in survival."* To do this, they compiled time series of annual SAR estimates for many populations derived from CWT and PIT data. They then used these SAR estimates in two exploratory or descriptive analyses: (1) a visual (graphical) analysis of local and regional trends and (2) a statistical comparison of Snake River SARs with other populations for a recent 5-year period. They also included data series for PIT tags for some Columbia Basin stocks but noted the important difference between CWT and PIT tag data. The ISAB has previously reviewed the use of CWT and PIT tag data for estimating SARs (ISAB/ISRP 2011-1, ISAB/ISRP 2009-1). Specifically, CWT data can be readily adjusted for fishery take whereas such adjustment for PIT-tag based SAR estimates is more difficult. SAR estimated from CWT data represent potential survival (i.e., expected survival from smolts to returning adults plus harvested fish), while SAR estimated from PIT tags represent realized survival (i.e., survival from first tagging to returning adults). The extent of differences between CWT and PIT-based SAR estimates may vary substantively across populations due to differences in tagging locations and exploitation rates.

The trend analysis consisted of a graphical and qualitative comparison of regional SAR trends. This type of visual assessment is prone to subjectivity, which can hinder defensible interpretation. Also, changes in tagging and measurement methodology can add additional sources of uncertainty and potential bias when trends are examined over long timespans with multiple series. One approach is to carefully filter or adjust data to address methodological differences. Another more general approach is to employ a unified statistical approach that takes advantage of the power of pooled cross-section and time series data (see, for example, Deaton 1985, Wooldridge 2010, Butsic et al. 2017), or to take other rigorous statistical approaches (see Coronado and Hilborn 1998a, 1998b; Sharma et al. 2013; Ruff et al. 2017).

The SAR data assembled by Welch et al. (2020) can be appropriate for analyses of general trends and spatial patterns using justifiable statistical methods but regardless of the methods used, caution is needed with such analyses to not over-step and over-extrapolate the results beyond what is supported. General statements about patterns in SARs can be inferred. However, such trend analyses alone are insufficient, without other analyses and supporting information, to make claims about causal factors and the contribution of specific life-stage components of the SARs (ocean, freshwater) for specific populations. The analysis in Welch et al. is limited to visual inspection of time series (their Figure 2), visual inspection of medians (their Figs. 3 and 5), and comparison of SAR values within 95% CI (their Figure 4). Quantitative analysis in the paper is extremely limited. Welch et al. (2020) present a set of interpretations and conclusions, and they do not make sufficiently clear which are supported (at least to some degree) by the data and their analyses and which should be considered speculation. These are discussed further as part the ISAB's response to Question 2.

Interpretation of broad-scale analyses of SAR values beyond descriptions of general patterns (as in Welch et al. 2020) is challenging and necessarily limited because of multiple complicating factors, such as the differences in how SAR values are estimated among populations. Any analysis of SAR values across populations, especially comparing SARs between two locations, must be cautious in interpreting results because the purposes, methods, and tagging locations of the studies used to estimate SARs vary both across regions and across time within regions. This need for caution applies not only to the analyses in Welch et al. (2020) but also to other studies of differences in SAR values within the Columbia River Basin. Many aspects of tagging studies differ among rivers including tagging locations, smolt size, release date, proportion tagged, adult detection locations, fisheries management, ocean conditions experienced, and influence of marine mammals. While both CWT and PIT estimates of SAR include a portion of the freshwater phase, that portion varies by river basin, stock, and tag groups within stocks (ISAB/ISRP 2009-1, Northwest Power and Conservation Council Decision Memo 2013). Finally, the SAR data comes mostly from hatchery-produced populations and therefore analyses provide only limited information about survival of natural-origin Chinook salmon or the early stages of their life history. For all of these reasons, this means that SAR estimates are not always comparable, and data sets and time periods must be selected carefully to ensure a reasonable degree of comparability. Welch et al. (2020) essentially take the SAR values (and information on exploitation rates) as obtained from a number of sources and proceed uncritically with little information provided on the comparability of SAR values across populations.

In summary, the ISAB supports the idea underlying the Welch et al. (2020) paper of analyzing SAR estimates from many populations, but conclusions beyond general statements of broad patterns and trends require appropriate treatment of data and statistical methods. Most importantly, appropriate use of the data must clearly indicate which conclusions are supported by the analyses and which are more appropriately viewed as speculative and needing additional data or further analysis. While the data used by Welch et al. (2020) are reasonable for comparing general trends in SAR values across locations, their analysis lacks statistical rigor and their results cannot be used to infer cause and effect relationships; only very general statements are therefore supportable. For example, neither the data nor the analytical methods are appropriate for inference regarding the effectiveness of altering the freshwater components of survival.

3b. Response to Question 2

Charge Question: Were the conclusions drawn by Welch et al. (2020) supported by their results?

Welch et al. (2020) use their analytical results to address two important and highly relevant questions that lead to their conclusions:

a) What are SARs for Chinook populations in the Columbia Basin, and how do they compare with the 2-6% SAR goals and to SARs for other populations?

b) Why are SARs for Chinook populations in the heavily modified Columbia Basin similar to those from other systems, including more natural and pristine ones without dams?

At a coarse resolution, the conclusion of Welch et al. (2020) that SARs are low for Chinook populations in the Columbia system and other systems, including those with no dams, is supported by the data and analysis presented in the paper. To put these SAR values in perspective, Figure 1 shows a previously derived (not using the data in Welch et al.) relationship between recruits per spawner (Rsg/S) and SAR values for Snake River Chinook. Recruits per spawner is a measure of population-level productivity. While there is substantial variation, positive productivity (Rsg > 1, or ln(Rsg/S)>0 as in Figure 1) occurs with SAR values of 2.0 and higher, with many instances of positive productivity occurring with SAR values between 1.0 and 2.0. [Note that the y-axis in Figure 1 is on the natural logarithmic scale.]

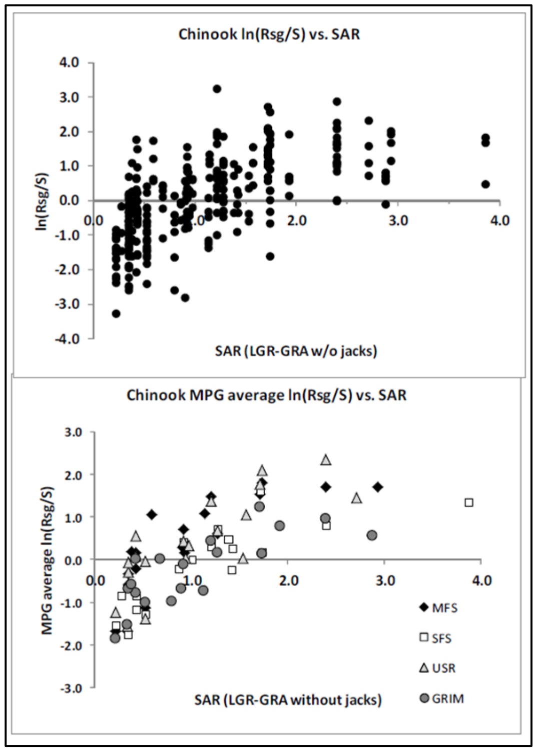

Figure 1. Association of spawning ground recruits/spawner and SAR for 17 Snake River spring/summer Chinook populations (upper panel), and by Major Population Group (lower panel) for brood years 1992-2010. (Figure 5.1 in FPC 2017). Note the log-scale for the y-axis.

Welch et al.'s more specific and strongly worded conclusion is, however, not supported. The authors state that "*Chinook salmon SARs have fallen to about 1% coastwide (ca. 1/3 of earlier levels).*" This implies a temporal trend for SAR values across systems that is questionable. Without the benefit of a comprehensive statistical modeling approach (see Appendix B), the validity of this conclusion cannot be assured. For example, as Welch et al. (2020) acknowledge, the Oregon Coast region exhibits relatively stable SARs with medians mostly in the 2% to 6% range (Figure 2 in Welch et al. 2020). Welch et al. (2020) attribute this to Oregon populations having a more southerly marine distribution. However, even this general statement requires careful wording when specific details are considered. For example, of the two Oregon populations Welch et al. (2020) include, one (Elk River) exhibits a southerly migration pattern while the other (Salmon River) exhibits a northerly pattern (Weitkamp 2009), yet both have similar levels of survival (Figure 3 in Welch et al. 2020). Welch et al. (2020) also note that some populations in the Columbia River Basin show increasing SAR values since the 1980's and early 1990s (Figure 2 and second paragraph on page 200 in Welch et al. 2020). This general conclusion by Welch et al. about coastwide populations should not be interpreted as the trend and magnitude of SAR for any specific population.

Welch et al. (2020) also concluded that results of CWT-based SAR methods differ to some degree with results of PIT tag-based methods. This has been documented in previous studies; some studies observed that PIT tag-based estimates of SARs are lower than CWT-based estimates (Knudson 2009, FPC 2018) while other studies found that PIT tag estimates are higher (Morrisett 2018). To provide additional clarity for readers, Welch et al. (2020) also could have further explained that the two approaches have very different purposes. CWTs are deployed largely for fishery and hatchery management purposes, and a great effort is expended to survey for them in the ocean fisheries so that exploitation rates for individual tag groups can be calculated. PIT tags were initially deployed to examine in-river survival through the hydropower system and can be used to separate freshwater versus marine contributions to SARs, but PIT tags are only extensively used in a few rivers throughout the West Coast.

The conclusion of Welch et al. (2020) that they found little evidence of dam-induced delayed mortality is weak because their analysis had low power to detect such effects. Welch et al. (2020) state, *"The PIT and CWT-based SAR estimates assembled here also fail to support the theory [of delayed mortality] because the SARs of Snake River populations are not reduced on average when compared to other regions."* While their analysis did not detect a delayed mortality effect, the SAR data as analyzed by Welch et al. (2020) have low power to detect such an effect and thus the likelihood of a false negative result (effect is present but not detected) is high. The Welch et al. paper presupposes that delayed mortality would be the only cause of differences in SAR values among these populations; other differences could easily mask this effect. Welch et al. (2020) provide no evidence that their analysis would have sufficient statistical power to detect delayed mortality, and the wide variation in estimates in their Figures 3 and 5 suggest that such power would be very low.

Another conclusion that lacked empirical support was Welch et al.'s discussion about why SARs in the heavily modified Columbia Basin appear similar to those from other systems, including systems considered degraded and systems without dams. Welch et al. (2020) use this result to conclude that the opportunity is limited for improving SARs from freshwater survival improvements for populations in the Columbia Basin. Welch et al. (2020) state:

> *"Given the geographically widespread collapse in survival to numerically similar levels and the steadily increasing effort devoted to survival monitoring for salmonids (Figure 8), the fisheries community need to re-assess several core conservation assumptions. Of primary importance is the actual effectiveness of freshwater habitat restoration initiatives when northern populations with nearly pristine freshwater conditions have similar SARs."*

First, as noted by Welch et al. (2020), there are exceptions to the "widespread collapse," such as populations in the Columbia River Basin that showed increasing SAR values since the 1980's and early 1990s (their Figure 2 and their second paragraph on page 200). Second, the statement quoted above can lead people to wrongly conclude that freshwater habitat initiatives for specific locations (e.g., Columbia River Basin) have been or will be largely ineffective. The leap from Welch et al. (2020) analyses of general patterns in SARs to conclusions about future effectiveness of freshwater restoration actions, especially specific systems, is not supported by the analyses. A number of issues lead to unacceptably high uncertainty including: (1) unknown data comparability, (2) inability to accurately isolate the freshwater component of the SARs, (3) lack of statistical rigor in analyses, (4) vagueness in the conclusions, and (5) SARs are primarily from hatchery releases, which are largely unaffected by freshwater restoration. In addition, their analyses are limited to Chinook SARs while habitat restoration may have many ecological benefits beyond that encapsulated in a single aggregate SAR value.

A major source of uncertainty that limits confidence in the Welch et al. analysis for informing the effectiveness of efforts to improve freshwater survival rates is the inability to separate freshwater contribution from the marine contribution to SARs, especially for specific populations, without invoking untested and likely invalid assumptions (see Appendix A). While the ISAB agrees that ocean conditions when smolts enter have a strong influence on overall survival (e.g., Wells et al. 2012; Satterthwaite et al. 2014; reviewed by Quinn 2018), the assumption that the marine component of SARs must be very similar across populations (or other untested assumptions to permit comparisons of the freshwater component) is unknown and unlikely. Welch et al. acknowledge that there can be substantive differences in ocean survival rates among populations due to their marine distribution and use the SAR trend and distribution information for two coastal Oregon subyearling populations as an example (top paragraph, p. 12).

It is important to note that SARs come from populations that experience different migrations in rivers from their point of release to the ocean, different body sizes at release, and many other location-specific effects and other factors not controlled for in the Welch et al. (2020) method of analysis. Such factors introduce considerable uncertainty into any comparisons. The ISAB describes a more comprehensive, unified statistical approach that can be applied, with the addition of more variables, to the kind of cross-section and time series data of SAR values assembled by Welch et al. (see Appendix B). Such analyses would make it possible to obtain robust results about the relationships between variations in SAR values and a range of underlying explanatory variables (see Appendix B). However, because of the multiple sources of uncertainty, CWT-based SARs are not reliable for examining the effectiveness of efforts to improve freshwater survival for specific populations.

Lack of clarity by Welch et al. (2020) in their statement of conclusions adds uncertainty and opportunity for misinterpretation of their paper. The Welch et al. (2020) paper is vague about whether their conclusion about the effectiveness of freshwater survival improvements is about: a) historical actions related to changes in hydrosystem passage (e.g., flow, bypass), b) future changes in hydrosystem passage and freshwater habitat restoration, or c) just future freshwater habitat restoration projects (e.g., addition of large wood, riparian planting) and not hydropower passage. Some Columbia Basin stakeholders, like the Northwest River Partners, assumed Welch et al. (2020) was addressing questions related to hydrosystem passage (a and b), as evidenced by their press release, which stated that the Welch et al. paper showed that:

> "*Dams, while having some effect on salmon survival, do not appear to be a key limiting factor for recovery*."

Welch's response to the FPC review (Welch et al. 2021) provided some clarification by stating:

> *"Despite the importance of the ocean, we [Welch et al.] do agree that salmon need good freshwater habitats. In the past, many rivers were degraded by human activities. It took great effort to reverse the damage and continued vigilance is still necessary. Our intention is not to detract from these achievements or to discourage freshwater restoration when it will benefit salmon*."

However, the statements related to freshwater habitat restoration remain vague in the published Welch et al. (2020) paper. Furthermore, in a letter to Northwest governors and the US Senate and Congress (March 17, 2021), Welch claimed the analysis in their paper indicates that removal of Snake River dams will have no consequential effect on the future salmon abundance. This suggests a broad definition of freshwater habitat restoration that includes not just changes in physical habitat and aspects of hydrosystem operations, but also the presence of dams.

Even if one restricts the definition of freshwater habitat improvement to just physical habitat restoration, SAR values used by Welch et al. (2020) are primarily from hatchery releases, which are not appropriate indicators for such efforts. Habitat restoration would also benefit spawning success and fry-to-smolt survival, which are not reflected in the SAR estimates used in Welch et al. (2020). Furthermore, habitat restoration would largely benefit naturally-produced salmonids that have a longer residency period in freshwater (coho, steelhead) and naturally-produced Chinook populations. Chinook yearlings released from hatcheries migrate downstream relatively quickly after release, with much of their freshwater use being restricted to the mainstem where fewer physical restoration efforts are conducted. SARs from sub-yearling hatchery releases would spend more time in freshwater, but they still would get less benefit from physical habitat restoration efforts compared to naturally-produced Chinook and other species.

The Welch et al. (2020) analysis is restricted to SARs of Chinook populations dominated by hatchery fish and therefore is not informative about freshwater habitat actions designed for other species, and habitat actions should be evaluated for their full breadth of ecological benefits. Focusing on a set of incomplete and single-species benefits mischaracterizes the overall effectiveness of freshwater habitat initiatives.

The ISAB response to this charge question is that the general conclusion by Welch et al. (2020) that SAR values are low and below 2% in many populations in the Northwest is well supported by their analysis but that such general statements should then not be associated with specific populations. Furthermore, the conclusions about the effectiveness of freshwater habitat initiatives are not supported empirically by the analyses and are speculation that would require further investigation.

3c. Response to Question 3

Charge Question: Does the ISAB have recommendations to improve the current analysis and interpretation of SAR values in the future?

The Welch et al. (2020) assembly of SAR values offers an opportunity for broad analyses of temporal and spatial patterns in SAR values. Such information is useful for providing a regional view of the time history of Chinook SARs across many populations. Assuming the analyst's interpretation will be restricted to what is supportable using SAR values, there are several ways to improve the analysis of the SAR data.

First, for purposes of visual inspection and comparison, more can be done to make the data comparable over time and across populations. The specific details of each population, such as age-of-entry (i.e., stream-type vs. ocean-type), length of river migration, duration of marine residence, number of dams, harvest and stocking history, and other population-specific characteristics, should be documented and added to the SAR dataset.

The second way to improve the analyses of the SAR data, along with an expanded set of explanatory variables — including the kinds of population-specific explanatory variables just mentioned — is to employ more sophisticated methods such as pooled cross-section and time-series data analysis (see Appendix B). These methods were not explored by Welch et al. (2020). Such methods address several common sources of potential bias likely to arise with observational data (Butsic et al. 2017). These sources of bias include a) the omission of explanatory variables (e.g., characteristics of freshwater habitat), b) mismeasurement of variables (e.g., SAR measurement between use of PIT versus CWT, or the use of SAR estimates from populations that include or exclude different portions of the salmon's life cycle), and c) the inclusion of explanatory variables that are not independent of the dependent variable (e.g., predation, harvest, or factors that would give rise to compensatory rather than additive changes in survival, or other "endogenously determined" variables). These widely used statistical methods are designed for such data (see Deaton 1985; Hausman and Taylor 1981; Wooldridge 2010) and would have benefits over the more piece-wise analyses done by Welch et al (2020). Future analyses of SAR values should look for spatial and temporal patterns and relate those to well-characterized explanatory variables and should also explore the use of other statistical methods. Future analyses of the SAR dataset, expanded with explanatory variables, could greatly add to the scientific community's and policymakers' understanding of the factors associated with spatial and temporal variation in SAR values.

The third way to improve the analyses is to base conclusions about the efficacy of past or future freshwater habitat initiatives in the Columbia River Basin on their effects on freshwater survival rates (e.g., reach-specific estimates based on PIT tag detections) rather than solely on the aggregated measure of survival provided by SAR values (e.g., Skalski et al. 2014, Deng et al. 2017). Our recommendation of using the more appropriate available data (PIT tags when available) is consistent with the approaches used by the FPC. With analyses like Welch et al. (2020), compromise is required to ensure enough different systems are included in analyses, at the expense of using sub-optimal information for data-rich systems.

Welch et al. (2020) recommend that more research be conducted on the causes of marine survival. The ISAB concurs that there are very good reasons for better understanding conditions in the marine environment and their potential effects on survival (ISAB 2007-2, ISAB/ISRP 2009-1, ISAB/ISRP 2016-1, ISAB 2017-1). Information on marine survival is helpful so that decision-makers are aware of the return on investment from hydrosystem operations and habitat actions, and can inform the life cycle modeling that evaluates population responses to habitat improvements. If data comparability, statistical methods, and other issues are addressed, then marine survival relevant to specific systems can also be used to improve broad scale (like Welch et al. 2020) and population-specific analyses of SARs. It is important to acknowledge that many factors affecting marine survival are either largely beyond management control (e.g., prey supply in the North Pacific, abundance of predators) or are constrained by other factors (e.g., purposeful reductions in harbor seal and sea lion populations, reductions in releases of hatchery-produced pink salmon). Better understanding marine survival is useful to put bounds on possible population responses to different combinations of management actions.

The ISAB notes that the current approach for management rightly focuses on understanding and testing actions that are under management's control and can therefore be manipulated. This emphasis is consistent with the goals of the Adaptive Management process used by the 2014 Program (NPCC 2014), which aims to reduce uncertainty about the effectiveness of management policies, rather than to reduce all scientific uncertainty. Additional analysis within a full life cycle framework, informed with better understanding of marine survival, will provide better guidance for management actions and will help policymakers and the public develop realistic expectations of likely population responses to specific management actions.

3d. Response to Question 4

Charge Question: Are the criticisms raised by the Fish Passage Center supported by the evidence and do any of those criticisms weaken Welch et al. (2020) results or conclusions?

The FPC review raises numerous criticisms of Welch et al. (2020) treatment of the data, analyses, and interpretations. The FPC review describes a mix of technical issues that are not likely to have a large effect on the results about broad patterns in SARs and issues that call into question the interpretation and conclusions made by Welch et al. (2020). Welch et al. responded to these criticisms in a rebuttal memo (Welch et al. 2021).

The ISAB generally concurs with the major criticisms of the Welch et al. (2020) analysis raised by the FPC review but concludes that, with better statistical methods and proper and more careful interpretation of results, the Welch et al. analysis can provide a useful large-scale (coast-wide) context to SAR values. The ISAB and FPC reviews share concerns about issues with the data treatment and analytical methods, and with the mixing of supported and speculative conclusions.

The FPC's comment about the need to use comparable data in this type of analysis is particularly important. If the values of SAR are to be used to make inferences across populations, then there must be careful consideration of which populations are used in the analyses, how the data are collected, and how the SARs are estimated. Welch et al. (2020) essentially used the other populations as controls to compare with the "treated" (affected by freshwater initiatives) populations from the Columbia Basin. However, if this comparison is used to make inferences about temporal patterns in SARs, then the control populations should be similar to those in the Columbia Basin with respect to both freshwater and marine characteristics (other than those impacted by dams and flows) and their sampling methods. Welch et al. (2020) did not sufficiently filter the data to exclude populations that were not appropriate controls for comparing to the Columbia Basin populations.

We also agree with the FPC's comments about the need to consider studies that have specifically focused on evaluating the effects of freshwater conditions on SAR. This comment has the same foundation as the ISAB's concern that Welch et al. (2020) do not use direct or indirect estimates of freshwater survival rates and therefore have no basis for commenting on effectiveness of past or future freshwater survival initiatives on Columbia Basin populations. The first response from Welch et al. (2021) to this FPC comment is that correlative analyses between freshwater conditions and SAR does not imply a cause-effect relationship. We agree with this tenet of scientific causality but note that the Welch et al. (2020) paper makes an equivalent assumption when they infer that the similarity in SARs from populations in the Columbia Basin and other systems are due to similarities in both freshwater and marine survival rates. They have not empirically established the cause for any similarities of the SAR values across systems documented in the paper; nor have they provided evidence for other assumptions needed to attempt to infer freshwater survival from SAR values for specific populations.

The Welch et al. (2021) rebuttal to the FPC concern about not considering freshwater conditions in their SAR analysis is based on a comparison of freshwater survival rates between Chinook populations from the Sacramento and Columbia Basins. This response is informative, but the data and analysis are not included in the Welch et al. (2020) paper. More definitive conclusions on the importance of freshwater survival rates of Chinook populations in the Columbia Basin require peer review of the new analysis presented in Welch et al. (2021). Welch et al. (2021) response to this FPC comment underscores the ISAB's recommendation to evaluate hydrosystem and habitat effects using differences or changes in freshwater survival rates, rather than using SAR values.

We want to highlight one response from Welch et al. (2021) to emphasize a critical element of our review:

> *What we (Welch et al. 2020) did say—and still stand by—is that if regions with excellent freshwater habitat have the same low SARs as regions with compromised freshwater habitat then the common problem must be in the ocean, not freshwater.*

While this statement can be generally true (note the important IF and assuming the "common problem" is the cause of the low SAR values), the key here is that the ISAB questions whether the analyses reported in Welch et al. (2020) can be used to support the statement. We reiterate that Welch et al. (2020) do not compare estimates of either freshwater survival rates or marine survival rates *per se* from populations from the Columbia Basin with other systems. Thus, there is a large unaddressed uncertainty in going from the analysis of SARs as done in Welch et al. (2020) to the conclusions in their statement about the role of ocean versus freshwater habitat effects. Information on how marine and freshwater survival components vary among locations is needed to evaluate this statement and infer potential population responses to changes in freshwater conditions for specific populations. The authors conflate the general consensus that marine survival rates are low with the assumption that the decrease in marine survival has been similar across all populations, an assumption that is not supported by data presented in the paper.

We also agree with FPCs criticism of the lack of a quantitative framework for evaluating effects (FPC comments 6 and 10). As an example, the FPC mentions that estimating a common year effect would be useful. Considering the implications of the policy recommendations provided in Welch et al. (2020), methods that are more rigorous are needed to quantify potential effects causing differences in SAR among populations and over time. We go further than the FPC and provide an example of a statistical modeling framework (Appendix B) to illustrate how such analyses could be done going forward.

3e. Response to Question 5

Charge Question: What are the management implications of the ISAB's conclusions and recommendation?

The ISAB agrees with the general claim of Welch et al. (2020) that current SARs for Chinook populations are low and below 2% in many years and populations. Chinook salmon tend to exhibit lower marine survival than other salmonids but compensate for it in other phases of the life history (notably, higher fecundity and higher survival of embryos during incubation). We agree that management actions should — and likely do — consider the low (and well documented in many studies) values of SARs and the role played by marine survival in a full life cycle approach. Low SAR values due to low marine survival can affect the long-term merits of freshwater management actions in multiple ways. Low SAR values will raise the cost of increasing the number of returning adults either from hatcheries or as a result of habitat improvements. Low SARs may also lower fish abundance overall, in which case the social value or benefit derived from actions aimed at offsetting those declines with habitat improvements or with hatchery production would also be greater.

However, the effectiveness of freshwater survival initiatives to increase adult returns for Columbia Basin Chinook populations has not been determined in the Welch et al. (2020) paper. If low marine survival is the dominant cause of low SAR in Columbia Basin Chinook populations, then such information can constrain population responses but does not imply (as Welch et al. 2020 conclusions can be interpreted as saying) that further management actions are futile or unwarranted. Welch et al. (2020) do not acknowledge or consider the legal responsibilities of Columbia River managers to manage the hydrosystem and mitigate for detrimental impacts to ecosystems and sovereign nations. Anadromous fish production throughout the Columbia River Basin is below historical estimates of natural production (ISAB 2015-1, Columbia Basin Partnership Task Force 2020) due to past and present modifications to the river system. Treating the current state of the Columbia River as the new normal for anadromous fish ignores the long history of cumulative modifications to the river and treaty responsibilities to sovereign nations.

Welch et al. (2020) do not distinguish between the effects of hydrosystem passage and operations and physical habitat restoration on the efficiency of producing adult returns and on proportional gains in adult returns. Proportional gains may contribute to broader goals for the Chinook populations in the Columbia Basin even if the total number of returns continues to be low due to conditions at sea. For example, management actions (e.g., hydrosystem or physical habitat changes) that result in a 20% increase in freshwater survival rate following density dependence will on average result in a 20% increase in adult returns, regardless of how low the marine survival rate is. Such proportional increases have the potential to slow or halt the rate of decline of currently unproductive populations or accelerate the rate of recovery for more productive ones, which are prominent in the stated goals of the Columbia Basin Fish and Wildlife Program (NPPC 2014). The ISAB previously recommended refining the 2-6% SAR goals with SARs needed to achieve recovery or harvest goals (ISAB 2018-3). Achieving target SAR values is an important quantitative objective of the Columbia Basin Fish and Wildlife Program, but there are many other quantitative and qualitative objectives for both anadromous and resident species (NPCC 2020).

Welch et al. (2020) question whether the Fish and Wildlife Program's objective of 2-6% SARs is attainable and realistic. They cite the study of spring/summer Chinook in the Snake River by Marmorek et al. (1998) and conclude,

> *"Although not explicitly stated, this seems to be the basis for setting the 2%–6% rebuilding standard for the Columbia River."*

Welch et al. do not consider the CSS (Comparative Survival Study) reports and publications that examine the relationship between SARs and recruits per spawner and that have found that SARs for Chinook frequently exceed 1%, sometimes 2-4% (FPC 2017). The ISAB has reviewed the 2-6% SAR objective of the Fish and Wildlife Program (ISAB 2017-2, ISAB 2018-3) and concluded that SARs less than 1% consistently result in generational decreases in abundance while SARs greater than 2% resulted in generational increases in abundance (see Figure 1 above). The ISAB concluded that 2-4% provide a readily measured, first-order objective for restoring stocks (ISAB 2018-3). Further, it is important to recognize that the rebuilding objective of 2-4% SARs is for all salmon species and steelhead, not just Chinook salmon.

The conclusion of Welch et al. (2020) that conservation actions to restore freshwater habitats are not likely to improve salmon returns is also based on the current low marine survival continuing. They do not address the potential for ocean regimes to improve and the value of restored freshwater habitat for recovery of Chinook populations during periods of improved ocean conditions. Ocean conditions are cyclical and climate change is not the only factor that determines trends in ocean productivity. This conclusion also disregards projections from Chinook life cycle models that indicate freshwater habitat influences projected adult returns and reduces estimates of quasi-extinction probability (NOAA 2017; Zabel and Jordan 2020). Any strategy for freshwater habitat protection and restoration should consider the uncertain future ocean conditions as part of a full life cycle perspective. However, without further analyses, the Welch et al. (2020) analysis does not provide an evaluation of the role of freshwater habitat restoration in improving adult returns of anadromous salmonids in the Columbia River Basin under uncertain future conditions.

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Appendix A. Limitations of the Welch et al.'s analysis for determining the effectiveness of freshwater habitat actions.

This appendix explains in more detail why the Welch et al. (2020) analysis of SAR values should not be used to make conclusions about the effectiveness of freshwater habitat actions. Such extrapolation of results requires invoking unlikely and untested assumptions. We use one such assumption of constant marine survival to illustrate. Consider that SAR is the product of a variable portion of freshwater smolt survival during downstream migration (Sjfw), marine survival which includes losses from harvest as well as natural mortality (Smar), and a variable portion of adult freshwater survival during upstream migration (Safw); thus, SAR = Sjfw x Smar x Safw. For simplicity of argument, we combine Sjfw and Safw into an overall freshwater survival rate (Sfw), or SAR = Sfw x Smar. In the Welch et al. (2020) dataset, the extent that freshwater survival is included in the SAR values varies among populations.

The ISAB concerns about the Welch et al. (2020) results being used to infer that there is low potential for freshwater habitat improvements to influence salmon recovery in specific locations are as follows. The Welch et al. (2020) analyses are a comparison of the SARs of two populations (e.g., a reference unregulated system (control) versus Snake, their Figure 3). Assuming they can show with sufficient confidence that $SAR_{control} = SAR_{snake}$, then one can say $Sfw_{control} \times Smar_{control} = Sfw_{snake} \times Smar_{snake}$. Since Welch et al. (2020) are attempting to make inferences about differences in freshwater survival rates between the two populations, but do not present direct estimates of those rates, the comparison of freshwater survival rates is inferred (i.e., Sfw = SAR/Smar) and is a comparison of two ratios.

$$SAR_{control}/Smar_{control} = SAR_{snake}/Smar_{snake}$$

Note that only SAR values are available and used by Welch et al. (2020) in their analyses. To infer, as done by Welch et al., that similarity in SAR values imply similar freshwater survival (i.e., similar Sfw values), they would need more information, such as the estimates of Smar. Thus, had Welch et al. (2020) shown that both SAR and Smar for populations in a reference system and the Snake were similar, their conclusion that freshwater survival rates were also similar would have been supported. They did provide a brief review of the some of the many studies that have documented low marine survival rates (top of p. 12), but they never compared Smar for populations in the Snake or Columbia Basins with other populations. They do acknowledge that Chinook populations from southern Oregon and California likely have higher marine survival than other populations owing to differences in marine migration patterns. However, their conclusion that freshwater survival rates for Columbia River Basin populations and those from more natural streams (i.e., less hydrologically altered) are similar assumes that marine survival rates are equivalent. Welch et al. (2020) do not evaluate the extent of differences in Smar among populations used in the analysis and its potential relative influence on their conclusion. Their conclusion about the limited scope for improving Sfw for Columbia Basin populations is therefore conditional on the unsupported assumption that Smar values for all populations in the analysis are similar and that current adverse marine conditions will uniformly continue or worsen. The same argument applies to other possible assumptions for interpreting freshwater survival (Sfw values) from SAR values, which also remain untested.

Appendix B. A general framework for analysis of pooled cross-section and times-series data

The ISAB recommends (as part of the response to question 3) that further analyses of the SAR data investigate the use of more comprehensive and unified statistical models and methods that are widely used in settings with pooled cross-sectional and time-series data. Such an approach is illustrated here in general terms for clarity and is not meant to be prescriptive; the formulations of the specific components of the analysis are general and can accommodate many possible relationships (e.g., nonlinear).

Welch et al. (2020) assembled SAR data for a large number of Chinook salmon populations covering a broad geographic scale over many decades. Data of this kind can be a powerful tool to ask a range of questions about the differences between and changes in SAR values for salmon populations. Indeed, analysis of data synthesized from multiple sources is a mainstay for research in economics, ecology, climatology, and other disciplines where non-experimental data (sometimes called "observational data") are the primary or only option for empirical research, and where large cross-sectional and time-series panel datasets are available (Deaton 1985; Hausman and Taylor 1981; Woolridge 2010). Welch et al. (2020) relied on simpler methods and did not take advantage of more sophisticated statistical techniques designed for these type of data. The ISAB recommends that future analyses expand the set of explanatory variables thought to influence SAR values, such as length of river migration, number of dams, and the geographical distance between ocean entry points.

The central goal and challenge in this kind of empirical research is to associate changes or differences in the outcome or dependent variable (SARs in this case) with changes or differences in the other variables (e.g., harvest, length of river migration, number of dams, duration of marine phase). However, to have confidence that the variation in the outcome variable can be used to infer the influences of explanatory variables, researchers must know how the outcome variable reflects the effects of the explanatory variable of interest and must account for the influences of other explanatory variables simultaneously by including them or "controlling for" their effects. Otherwise, the changes in the outcome variable do not provide information that allows for deducing the effects of specific explanatory variables. In our assessment of the Welch et al. paper (2020), there are three main types or sources of biases: (1) omission of explanatory variables such as measures of freshwater habitat characteristics, location-specific ocean conditions, and presence of dams, (2) mismeasurement of variables, such the use of SARs estimates that include or exclude different portions of the salmon's lifecycle, and (3) inclusion of explanatory variables that depend on each other or the outcome variable (i.e., endogenously determined, Wooldridge 2010). For example, harvest levels can depend on the adult population, which influences the calculation of SAR.

A unified modeling approach will require: (1) including or accounting for all important independent explanatory variables (continuous, categorical, and binary), (2) addressing potential specification problems presented by endogeneity (i.e., feedback effects from explanatory variables that are influenced by the dependent variable; for example, harvest that changes in response to salmon abundance), and (3) controlling for unmeasurable or unobservable variables (e.g., using a two-factor fixed effects regression model) (Wooldridge 2010).

This general approach is presented here in more technical detail for completeness and described with some specificity to the current situation of analyzing SAR data. Define the number of returning adults in the population (not only the sampled adults) as A_{it} in system *i* and for cohort-adjusted period *t* (referring to period t rather than year t to imply that for variables influencing survival at different life stages, the appropriate year for a given cohort is implied to be a year or years earlier than the adult return year). The model has A_{it} as a function of the population of smolts S_{it} in system *i* and cohort-adjusted period *t*, and a matrix of other independent variables $\boldsymbol{X}_{it}$ that influence survival in a given system in a given cohort-adjusted (corresponding) period. We can write this as:

$$A_{it} = \alpha + S_{it}\mathbf{X}_{it}\boldsymbol{\beta} + \mu_i + \delta_t + \varepsilon_{it} \qquad [1]$$

Because some factors influencing survival in system *i* during period *t* are not measurable or observable, we recognize μ_I as system-specific fixed effects that are invariant for system *i*. Similarly, we identify δ_t as time-period-specific factors that affect all systems in period *t* (e.g., ocean conditions), and $\mathbf{X}_{it}$ is a matrix of independent factors influencing survival. Our interest is in the estimated values in vector $\boldsymbol{\beta}$, which we know will be biased if, in addition to the common assumptions, μ_I or δ_t are associated with the error term ε_{it} (the expected value of $\mu_i\varepsilon_{it}$ or $\delta_i\varepsilon_{it}$ is not zero for all X_{it}). Alternatively, in some settings an approach employing random effects will be advantageous.

However, the two-way fixed effects model described above is not estimable because we do not have data on populations A_{it} and S_{it}, we only have tagged fish from cohort $\hat{S}_{it}$ selected from S_{it}, and a corresponding sample of tagged captured adult fish, $\hat{A}_{it}$. For these samples, we can write:

$$\hat{A}_{it} = \alpha + \hat{S}_{it}\mathbf{X}_{it}\boldsymbol{\beta}_1 + \hat{S}_{it}\mathbf{Z}_{it}\boldsymbol{\beta}_2 + \mu_i + \delta_t + \varepsilon_{it} \qquad [2]$$

where additional factors in $\boldsymbol{Z}_{it}$ influence the relationship between the sampled/tagged smolts and the sampled/tagged adults. These factors include the tagging technology (CWT versus PIT), the timing of tagging and release (which will adjust or control for differences in the measurement of SARs, the outcome or dependent variable), factors related to whether the tagged fish are wild or hatchery, etc. These additional factors will contribute to variation between sampled smolts and sampled adults. So, again, our estimates of parameters of interest in $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_2$ will be biased if μ_I or δ_t are associated with the error term ε_{it} (the expected value of $\mu_i\varepsilon_{it}$ for all X_{it} is not zero) in this new equation for the relationship between sampled smolts and sampled adults.

A third category of bias comes from endogeneity due to feedback effects or dynamic effects. For example, in equation [1] above the dependent variable A_{it} is a function of the independent variable smolts, S_{it}. There are elements in **X** and **Z** however that are not independent of A_{it} (i.e., adult abundance) such as predation P_{it} or harvest H_{it}. Additionally, smolts in period t are a function of female spawners, $\boldsymbol{F}_{it-n}$, from a previous cohort. These feedbacks mean that adult abundance A_{it} described in equation [1] is actually determined by a set of simultaneous and dynamic relationships, ones we might characterize with general terms in the following way:

$$
\begin{aligned}
A_{it} &= \alpha + S_{it}\mathbf{X}_{it}\boldsymbol{\beta}^{A} + \mu_i + \delta_t + \varepsilon_{it} && \text{(adults)} \\
P_{it} &= \alpha + A_{it}\phi_i + S_{it}\gamma_i + \mathbf{M}_{it}\boldsymbol{\beta}^{p} + +\mu_i + \delta_t + \varepsilon_{it} && \text{(predation)} \\
H_{it} &= \alpha + A_{it}\eta_i + \mu_i + \delta_t + \varepsilon_{it} && \text{(harvest)} \\
S_{it} &= \alpha + F_{it-1}\mathbf{X}_{it}\boldsymbol{\beta}^{S} + \mu_i + \delta_{t-1} + \varepsilon_{it} && \text{(smolts)}
\end{aligned}
\qquad [3]
$$

The superscripts on the βs in [3] indicate the three different vectors of parameters estimated for each of the equations. The parameters ϕ and γ are estimated coefficients. Predation *P* is a function of concurrent smolt and adult abundance and a matrix of other factors, **M**. Harvest *H* is a function of adult abundance, and smolts S in period t is a function of female spawners in the previous period and other system factors. This endogeneity means that the coefficients estimated in $\boldsymbol{\beta}$ will be inconsistent estimators (persistently biased) (see Gordon 2015; Thorson and Kristensen 2016).

One other potential source of bias deserves mentioning, but it may have a small effect. In the case of data for hatchery Chinook, the location and other attributes of hatcheries will not be distributed randomly in terms of geography or other characteristics across the set of wild fish systems that are of interest to society. To the extent that this represents a kind of selection bias, this can also lead to biased estimates (Heckman, 1979); for example, in the trends over time in SAR values.

There are methods for addressing these kinds of endogeneity and dynamic relationships that can also add structural specification of the terms in the model (see Butsic et al. 2017), but addressing or estimating these simultaneity and dynamic relationships is challenging. These dynamic relationships make clear that some of the ways in which adult abundance in a given system changes over time are not reflected in the SAR metric. Equation [2] can be dividing by $\hat{S}$ and reorganized to separate the independent continuous variables $\mathbf{X}_{it}$ and dummy variables $\boldsymbol{D}_{it}$ so that we have:

$$SAR_{it} = \frac{\hat{A}_{it}}{\hat{S}_{it}} = \alpha + \mathbf{X}_{it}\boldsymbol{\beta}_1 + \mathbf{D}_{it}\boldsymbol{\beta}_2 + \varepsilon_{it} \qquad [4]$$

The measured SAR for system *i* will not reflect the full influences of the simultaneous and dynamic relationships in [4], so that in a given period t, or over the period between t-n and t, it will be very challenging to determine whether SAR, or changes in SAR reflect changes in system abundance (*A* and *S*) or only changes in $\hat{A}/\hat{S}$.

The ISAB recommends that future analyses for patterns and trends in SAR values, and identifying relationships between SAR and other variables, consider these type of statistical analysis methods. Such analyses would provide more robust results and thus more defensible conclusions.