Climate-Resilient Restoration and Mitigation Strategies for Columbia River Basin Fish and Wildlife

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Report Cover

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ISAB Members – Authors and Contributors

Courtney Carothers, Ph.D., Professor, Department of Fisheries, College of Fisheries and Ocean Sciences, University of Alaska Fairbanks

Patrick Connolly, Ph.D., Retired, Emeritus Research Fish Biologist at the U.S. Geological Survey, Columbia River Research Laboratory, Cook, Washington

John Epifanio, Ph.D., Former Principal Scientist with the Illinois Natural History Survey and Research Professor with the University of Illinois; now based in Portland, Oregon

Dana Infante, Ph.D., Professor and Chair of Department of Fisheries and Wildlife, Michigan State University

James Irvine, Ph.D., Emeritus Research Scientist, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, British Columbia

Yolanda Morbey, Ph.D., Professor, Department of Biology, Western University, Ontario, Canada

Thomas P. Quinn, Ph.D., (ISAB Chair) Professor, School of Aquatic and Fishery Sciences, University of Washington, Seattle

Kenneth Rose, Ph.D., France-Merrick Professor in Sustainable Ecosystem Restoration at Horn Point Laboratory of the University of Maryland Center for Environmental Science

Desiree Tullos, Ph.D., P.E., (ISAB Vice-Chair) Professor at Oregon State University, Biological and Ecological Engineering Department

Ellen Wohl, Ph.D., Professor of Geology and University Distinguished Professor, Department of Geosciences, Colorado State University, Fort Collins

Michael Young, Ph.D., Emeritus Research Fisheries Biologist, Rocky Mountain Research Station, U.S. Forest Service, Missoula, Montana

ISAB Ex Officios and Manager

Michael Ford, Ph.D., Senior Scientist, Northwest Fisheries Science Center, Seattle, Washington (note: retired before report was completed)

Kris Homel, Ph.D., Biologist for Program Performance, Northwest Power and Conservation Council, Portland, Oregon

Robert Lessard, Ph.D., Fisheries Scientist, Columbia River Inter-Tribal Fish Commission, Portland, Oregon

Erik Merrill, J.D., Independent Science Manager, Northwest Power and Conservation Council, Portland, Oregon

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Executive Summary

A changing climate in the Pacific Northwest continues to affect the Columbia River Basin's fish and wildlife, as well as the entire river ecosystem. The ISAB (2007-2) first reported on the effects and framed the concerns related to climate change nearly two decades ago. They observed that air temperature and precipitation had shifted over the past century globally, regionally, and throughout the basin. Among other key findings, they noted that climate models predicted that air temperatures would continue to increase, leading to warmer summer water temperatures, earlier spring floods from melting snow, and more frequent winter floods as precipitation will tend to fall as rain rather than snow. These changes will have direct and indirect effects on the Columbia River Basin's fish and wildlife populations.

Two key goals of the current report are to examine new information available since 2007 and identify strategies and practices addressing climate change for fish and wildlife. Advances in analytical techniques and growing regional and global datasets have led to more spatially specific and precise projections of the likely atmospheric and environmental changes over the coming decades, enabling more refined assessments of how a changing climate will affect focal species, populations, and life stages. Beyond reviewing these advances, we synthesize the lessons that have been learned and the practical tools that have emerged as part of climate-resilient restoration in the Columbia River Basin.

We framed the focus of this report around three guiding emphases:

1. ecological resilience, which reflects *the capacity of a species or habitat to recover from a disturbance without the loss of ecological function;*
2. anadromous salmon, steelhead, and resident trout; and,
3. ecological dimensions rather than social, cultural, and economic dimensions of how changing climate affects human communities.

The changing climate and its effects on fish and wildlife in the Columbia River Basin since ISAB's 2007 report

Changes in atmospheric and hydrological conditions. Documented shifts in environmental conditions since the ISAB's 2007 report underscore the rate and magnitude at which temperature and hydrological patterns have changed over this short period (i.e., decades rather than centuries). The most evident shifts in the Pacific Northwest and Columbia River Basin have been:

- increases in mean air temperature, consistent with global patterns

- increases in mean inland water temperature
- accelerating air and water temperature increases, often occurring as extreme events, rather than gradual and continuous changes
- spatial variability and asynchrony in changes across the interior and coastal parts of Columbia River Basin, with interior areas generally experiencing more dramatic changes than coastal areas, and
- although less certain, altered precipitation patterns including 1) shifts in timing of annual precipitation to winter months, 2) increasing precipitation intensity, 3) increasing frequency of rain-on-snow events at high altitudes where snowpack persists (although rain-on-snow events will decrease at lower elevations due to snowpack declines), and 4) an earlier onset of winter and spring flows – all of which tend to alter river discharge patterns throughout the basin.

Frequency and magnitude of changes occurring in different locations across the Columbia River Basin. Climatic changes and their effects on ecosystems are occurring in different ways and at different magnitudes across the basin:

- In headwaters and small tributaries, rising mean annual and summer water temperatures, lower and more protracted summer baseflows, earlier snowmelt, and the headwater ascent of rainfall-dominated hydrology have continued.
- Analytical improvements have enabled better predictions of changes in habitat occupancy for many species, including migratory and resident fishes.
- In the basin's mainstem, climatic shifts are expected to exacerbate a history of changes in hydrological and thermal regimes resulting from land use and hydrosystem development.
- Throughout the tributaries and mainstem, altered temperature and hydrological profiles correspond with shifts in community assemblages, including spatial and numerical expansion of non-native warmer water predators and competitors.
- Long-lived, highly migratory populations of native freshwater fish will have increasing exposure to these climate-related shifts, including more frequent interactions with non-native taxa pre-adapted to warmer water. Resident species or anadromous runs whose life cycle spans multiple seasons, years, and locations will experience multiple climate-related and other human-caused stressors.
- In the estuary, monitoring has begun to address uncertainties raised in the previous ISAB report about the effects of climate change on salmonids in this large, complex transition

zone, including rising sea levels, saltwater intrusions, sediment recruitment patterns, storm surges, altered food webs, and predator expansions.

- In coastal ocean and nearshore marine environments, the rising frequency of unprecedented heat events (e.g., in 2015 and 2021) and other disruptions of the Pacific Decadal Oscillation and the El Niño/La Niña patterns offer insight into future stresses facing Columbia River Basin. Most management and restoration actions to mitigate climate change address the freshwater phases of salmon life cycles, understanding the role of ocean conditions can help adjust management during the freshwater phases, particularly in years of extreme heat.

Climate resilient planning efforts and tools used in the Basin

As the evidence and understanding of the effects of climate change in the Columbia River Basin has grown so have the variety, sophistication, and transparency of efforts to mitigate these effects on fish and wildlife. Notably, since 2007, improved climate modeling and effect predictions have contributed to the development and application of tools for more objective and transparent prioritization actions. These tools facilitate implementation of restoration and management actions that are cost effective, durable, and achieve objectives. Advances have occurred within the scientific community and leadership of the Columbia River Basin's Tribes who are developing strategies blending Indigenous and Western science perspectives. Some examples of these efforts include:

- **Tribal leadership in climate resilience assessment and planning.** We summarize examples of progress in climate adaptation and coordination led by Columbia River Tribes, including Upper Snake River Tribes (USRT), Upper Columbia United Tribes (UCUT), the Nez Perce Tribe, and Columbia River Inter-Tribal Fish Commission (CRITFC). Frameworks and tools include climate vulnerability and priority action assessments, adaptation toolkits, rangeland strategies, ecosystem resilience tracking, and searchable database for ongoing actions (e.g., Tribal Climate Resilience Action Database).
- **Emphasizing youth**. Some projects have recognized the need to engage the next generation, who will face the largest challenges from climate change. These projects are primarily led by tribes in the basin, and include community outreach and education programs, a program on collaborative problem-solving program, and other efforts to build the tools and professional skills youth will require to be the next climate resilience leaders.
- **Resist, Accept, Direct (RAD).** The framework aims to "help decision makers make informed, purposeful, and strategic choices" about how to invest resources in

ecosystems undergoing change through a transparent and collaborative approach. "Resist" involves working to maintain or restore ecosystem features and functions. "Accept" refers to a choice to let the ecosystem evolve without intervention. "Direct" involves activities that steer an ecosystem towards a specific outcome or desired state.

- **Habitat Assessment and Restoration Planning (HARP).** HARP is a life cycle-based framework that helps prioritize habitat restoration actions for salmon recovery and resilience. The framework identifies landscape-scale changes from climate change, land use change, habitat restoration, among others to show responses from proposed actions. It has been applied in multiple river basins in Washington.
- **Atlas Restoration Planning Framework (ATLAS) for the Grande Ronde watershed** is used to prioritize habitat restoration actions and climate-related risks, with updates incorporating attributes like water flow, temperature, land use, and fish habitat needs.
- **Climate resilience assessments.** Online tools, such as one developed for the Washington Coast (Climate Resilience Index), can be used to project future conditions and rank projects across salmon life stages. This or other assessment tools may contribute to prioritization by characterizing ecological resilience based on climate exposure, ecological sensitivity, and social adaptability. Similarly, the Expert Regional Technical Group (ERTG) for estuary habitat restoration uses evaluation criteria that affect climate resilience – such as connectivity and heterogeneity of functional habitats, life history diversity and redundancy of species, and links among ecological and human social systems.
- **Climate-inclusive conservation, especially in the Lower Columbia River.** Collaborative actions in the lower Columbia River and estuary, led by the Lower Columbia Estuary Partnership, have been guided by two conceptual approaches. "Climate-Smart Conservation" practices evaluate the ways actions can improve or mitigate climate impacts upfront rather than as an afterthought. The "Climate Adaptation Framework" aims to foster current patterns of biodiversity such as large intact natural landscapes and ecological processes and geophysical settings to maintain or reestablish climate refuges and facilitate movement between habitats.
- **Prioritizing refuge habitats against climate-related risks.** There is a growing appreciation of how small and headwater streams can serve as local thermal (cold-water) refuges during heatwaves and as climate refuges capable of sustaining some populations in the coming decades, particularly for reproduction and rearing. Efforts to identify, preserve or restore, and reconnect thermal refuges for migratory fish in large

tributaries are being undertaken to promote refuge duration, connectivity, and effectiveness.

- **Site-specific analysis and modeling tools.** Planning for climate-resilient habitat restoration and other practices is informed by integrating past adaptive management practices, expert opinion, environmental and biological data, and numerical models that estimate habitat and/or fish responses to future habitat or climate change scenarios. Many of these data sets, modeling tools, and information repositories can be readily accessed from websites.

On the ground approaches and practices

Several approaches and actions aimed at climate-resilient restoration and mitigation are presently used within the Columbia River Basin, as indicated by published literature and briefings to the ISAB. These include efforts to provide sustained, accessible cold-water refuges, and efforts addressing secondary effects of changing climate.

- **Increasing lateral and longitudinal connectivity.** Reconnecting river ecosystems longitudinally and laterally with their floodplains increases resilience by expanding access to and movement across environmental gradients, including access to refuges during extreme events. Increasing connectivity among fragmented habitats also gives organisms a wider array of habitats if access to historical quality habitats is lost.
- **Identify, maintain, and enhance cold water habitats and thermal refuges.** During extreme events, cold-water habitats and thermal refuges are needed for the persistence of freshwater life stages of most salmonids.
- **Conserving riparian shading and reducing thermal loads.** Shading from canopy cover is an important way to reduce solar-influenced thermal loads, especially in shallower tributaries and headwaters.
- **Actions that emphasize dynamism to support adaptation to changing conditions.** Practices such as levee removal and setback or reintroduction of large wood to initiate lateral erosion prioritize dynamism over stability and give rivers the space and materials to re-organize themselves as flow and sediment change.
- **Adjustments to water infrastructure and their operations**. Infrastructure operations can be adjusted to minimize their impacts that overlay climate change and mitigate the effects of climate change. Adjustments can support temperature management, improve fish passage, and induce flow variability that supports diverse life histories and seasonal timing.

- **Salvage and captive rearing.** While many of the ongoing actions are directed at habitat restoration or protection, under extreme circumstances, salvaging or rescuing populations of high-priority species under the immediate threat of extirpation may be the only viable option. This approach, however, is typically limited in scope and duration because of cost and logistics.
- **Additional actions not reviewed herein.** A number of other actions targeting climate resilience were not considered in this report, including those related to expansion of warm-water predators, evolving wildfire management, reduced harvest of overexploited populations, reduced hatchery releases for overcrowded populations, and carbon accounting in restoration planning.

Recommendations for climate resilient fish, wildlife, and river restoration practices

Examination and review of the many ideas and experiences across the Columbia River Basin led the ISAB to seven recommendations regarding climate-resilient restoration and mitigation. These recommendations represent our high-level responses to our review-charge questions:

1. **Strategic and transparent prioritization of actions that considers intersecting stressors is important at the outset of project planning.** Resource decisions should be made with strategy and transparency, through public engagement, and use available science-based information, including Indigenous knowledge. Strategies that do not fully consider other factors that intersect with climate change or address social dimensions may not produce the intended benefits over the long term.
2. **Maintaining and enhancing physical habitat and species' life history diversity are priorities for increasing climate resilience.** Restoration actions can support diverse life histories if they provide a dynamic set of habitats, connectivity, and other conditions that allow species and population to express their full suite of life history patterns.
3. **Climate-resilient habitats need more physical space, more temporal dynamism, and more innovative monitoring.** Restoration and mitigation are most likely to promote climate resilience when projects allow dynamic recovery rather than a static end-point, to the degree compatible with existing infrastructure. Modern technology and innovative thinking already exist to design and monitor these projects.
4. **Policy and regulations need to be adaptable and collaborative.** Policy needs to rapidly assimilate and use newly available climate information. Further, an important tension exists between risk averse regulatory guidance and the need for flexibility and innovation.

The transition to restoration and reciprocity that prioritizes dynamic areas with space to adjust over time will require projects to proceed faster and be scaled more broadly in their design and implementation. Project delays and costs attributed to regulatory requirements will need to be addressed.

5. **Considering reciprocity of actions through a Tribal ecological and cultural framework will promote climate resiliency.** Reciprocity is a core Indigenous value across many cultures and requires stewardship and care by people for the environment that in turn cares for the people (i.e., provides foods). Reciprocity is relevant to climate-resilient restoration in several ways, including sharing knowledge among people and organisms, using management actions to learn, and sharing of the burden of improving a neighbor's stream or river by all neighbors who are linked to that stream or river.
6. **Engaging a broader public constituency will increase the scale and benefit of projects.** Scientists and natural resource managers are working to communicate stories about their projects to the public in ways that foster understanding and motivate engagement. Examples of restoration projects with climate considerations are available and need more exposure.
7. **While some knowledge gaps exist, the current scientific foundation supports taking immediate action toward more climate-resilient restoration.** Important advancements have been made by scientists and managers since 2007, and adequate information and tools exist for implementing high-impact projects. However, we identify two broad priorities: 1) community-led efforts to identify the information needed to plan, prioritize, and act to save specific populations, and 2) a similar analysis to what is presented here for salmonids but for sturgeon, lamprey, and other native fishes.

Climate-Resilient Restoration and Mitigation Strategies for Columbia River Basin Fish and Wildlife

1. Background

1.1. ISAB Review Charge

On February 27, 2024, the ISAB's Administrative Oversight Panel[1] assigned the ISAB to produce a state-of-the-science report to synthesize a suite of potential best practices for planning, designing, and implementing restoration and mitigation actions in the face of climate change in the Columbia River Basin (see assignment description). The review charge is to provide a brief update of the ISAB's 2007 Climate Change Report (ISAB 2007-2), examine current efforts to address climate change to the basin's fish and wildlife, and describe the lessons learned.

The scientific and management literature, as well as individual projects within the Columbia River Basin, has matured greatly since the 2007 ISAB report and presently offer improved insights on how habitat restoration and other mitigation practices need to adapt to climate change. The Columbia Basin Tribes, state and federal agencies, NGOs, and the Council, for example, have incorporated climate change in planning, management, and restoration efforts. For recent Council and Independent Scientific Review Panel (ISRP) proposal reviews, project proponents were asked to describe how climate change could affect their project's goals and objectives, and the Council provided resources[2] to help the proponents address these questions. The ISRP (2022-1) found that the responses ranged considerably; some proposals had comprehensive and detailed approaches whereas others provided only general responses.[3]

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[1] The ISAB Administrative Oversight Panel consists of the Chair of the Northwest Power and Conservation Council, the Science Director of NOAA's Northwest Fisheries Science Center (in consultation with the NOAA Regional Administrator), and the Executive Director of the Columbia River Inter-Tribal Fish Commission (representing the Columbia River Indian Tribes).

[2] See the proposal template, Climate Change Information and Data Sources (pages 14-17), that was used for the Anadromous Fish Habitat and Hatchery Projects Review.

[3] Following the Anadromous Fish Habitat and Hatchery Projects Review, Council staff evaluated the extent to which project proposals covered the proposal questions on climate change, identified a few projects with exemplary approaches, and invited the proponents to present their approaches to the Council's Fish and Wildlife Committee: *Examples of climate change considerations in project planning and implementation* (June 2022).

This report's intent is to further synthesize lessons learned from these research, review, and management efforts in a way that decision makers, program developers, project proponents, and restoration practitioners can readily apply.

This review seeks to address the following questions and issues:

1. As the region's climate becomes more variable with warmer annual temperatures and altered precipitation and streamflow regimes, what spatial and seasonal patterns are expected across the Columbia River Basin? The changes and challenges described are not expected to occur uniformly across the basin. Rather, they likely will differ from headwater tributaries and downriver through the main channel and hydrosystem, the estuary, and coastal ocean.
2. In the basin, how have climate change projections and other planning tools been used in restoration or mitigation projects at the local to regional scale? What were the important challenges, constraints, and successes?
3. Building on the answers to Questions 1 and 2, what can be recommended regarding pathways or alternatives for making restoration and mitigation more ecologically resilient to the suite of climate-related challenges? Effective and responsive actions, and their cumulative and synergist effects, will explicitly address challenges to improve the long-term resilience of the basin. These challenges may include altered hydrology, air and water temperatures, drought and flood cycles, habitat, fire regimes, predation, and food webs as well as species invasions and changes in predatory birds and mammals, among others.

1.2. Review Methods

To conduct the review, the ISAB considered information from various sources within and beyond the basin. These included briefings from tribal, federal, and state agencies with restoration, mitigation, and management responsibilities (listed below) and a review of published literature (peer-reviewed and other reports) of best practices for planning and implementing restoration actions under climate change.

List of Briefings

Our review relies heavily on the set of briefings we received, and we are indebted to the presenters for sharing their work:

December 16, 2024

- Changes, challenges and progress since ISAB 2007 Report – Nate Mantua, NOAA (presentation link)
- Effects of climate change on salmon, strengths and weaknesses of our knowledge based on a literature review – Lisa Crozier, NOAA NWFSC (presentation link)
- Lower Columbia Estuary Partnership: Actions for Climate Change Resiliency – Catherine Corbett, LCEP (presentation link)

December 17, 2024

- Climate Adaptation Framework to Guide Salmon Habitat Protection and Restoration on Washington's Coast - Mara Zimmerman and Grace Adams, Coast Salmon Partnership and Foundation (presentation link)
- Salmon Vulnerability and Resilience to Climate Change – Tim Beechie, NOAA NWFSC (presentation link)

January 10, 2025

- Climate Action in the U.S. Fish and Wildlife Service: The Resist-Accept-Direct (RAD) Framework – J. Michael Hudson, USFWS (presentation link)
- Climate effects on PNW Streams and Fish Communities: Lessons Learned the Past 20 years – Dan Isaak, USFS Rocky Mountain Research Station (presentation link)
- Best Practices in Habitat and Species Monitoring, Modeling and Restoration for Climate Resiliency - Chris Jordan, NOAA NWFSC (presentation link)

January 17, 2025

- Climate Planning and Building Tribal Resilience in the Upper Snake River Basin – Scott Hauser, Executive Director, Upper Snake River Tribes Foundation (presentation link)
- Nez Perce Tribe Climate Pollution Reduction Program and Priority Climate Action Plan and Projects – Stefanie Krantz, Climate Change Coordinator, Nez Perce Tribe (presentation link)

January 30, 2025

- Columbia River Inter-Tribal Fish Commission and Yakama Nation Work on Cold Water Refuges and Restoration – Bill Sharp, Yakama Nation, and Charles Seaton, CRITFC (presentation link)
- Coeur d’Alene Tribe: Using Tribal Values to Develop a Climate Agenda – Laura Laumatia, Environmental Programs Manager, Coeur d’Alene Tribe (presentation link)

- Panel of restoration practitioners (link to recording)
    - Matt Cox, PE, Interfluve
    - Jon Ambrose, Environmental Science Associates
    - Marjorie Wolfe, PE, Wolfe Water Resources

February 18, 2025

- Grande Ronde Basin: Increasing Climate Resilience through Restoration and Habitat Protection – Jesse Steele, GRMW Executive Director, and colleagues (presentation link)
- Confederated Tribes of the Umatilla Indian Reservation Department of Natural Resources First Foods Management and Novel Climate Resilience Examples – Eric Quaempts, CTUIR Natural Resources Director (presentation link)
- Future Flows for the Upper Umatilla River – Scott O'Daniel and Bethy Rogers-Pachico, CTUIR (presentation link)

1.3. Report Framing

The presentations, case-studies, and peer-reviewed literature demonstrate the effort and innovation devoted to climate change effects in restoration projects by agencies and other organizations throughout the Columbia River Basin. This work is reported in peer-reviewed literature, organizational websites, and other media. We aimed to describe the range of ongoing ideas and actions to characterize what is known, where these actions are being undertaken and working, and any limitations and lessons learned. To do this, we framed the focus of this report around three guides:

1. **Emphasis on resilience.** To frame and ultimately confront the emerging stresses on ecosystems (Section 2.1), we attempted to consider experiences and theory through the lens of ecological ***resilience*** to environmental changes. Resilience reflects *the ability of a species or habitat to recover from a disturbance or change without the loss of function* (Adams and Zimmerman 2024, Gunderson 2000). This concept acknowledges that the biota and ecosystems will continue to adapt to changes in land-use, watershed alteration, and other anthropogenic effects. Consequently, restoration management should not focus on a static set of targeted outcomes.
2. **Emphasis on anadromous salmonids.** We focused primarily on Pacific salmon and steelhead in this report. We acknowledge the relevance of recent work on Pacific lamprey

and primarily non-anadromous salmonids (e.g., cutthroat trout, rainbow trout, and bull trout). We further note that a broader examination of additional fish species and other aquatic taxa, as well as a host of terrestrial species, is warranted for a broader ecosystem perspective. Changing temperature and flow patterns are affecting non-anadromous as well as anadromous salmonids, and the entire web of fish species throughout the basin will be affected by changes in environmental conditions. Nevertheless, the number and diversity of projects designed to aid anadromous salmonids, and the assessment of such projects, greatly exceeds those of other taxa, hence our focus on anadromous salmonids here. However, many of the concepts and principles we detail for salmon apply broadly.

3. **Emphasis on ecological dimensions.** This report does not attempt to fully address social, cultural, and economic dimensions of how changing climate affects human communities, especially Indigenous or other frontline communities whose cultures, spirituality, and lifeways are impacted by climate change (Hauser 2025 USRT presentation, USRT website, USGCRP 2023). Some relevant topics came up in our review and aspects of the key findings touch on how societal values impact prioritization of where action is required. However, despite the importance of these values in driving adaptations and prioritization of institutional investments, a comprehensive review of these human dimensions is beyond this report's scope.

Context from the 2024 ISAB review of the 2014 Fish and Wildlife Program and 2020 Addendum. While working on this climate report, the ISAB also completed a review of the Fish and Wildlife Program (ISAB 2024-2). That report concluded, "The frequency of warm years and the corresponding environmental conditions are expected to increase in the future. The survival of salmon may thus decrease more than recent averages illustrate. The collective ongoing poor survival of Columbia River salmon and steelhead warrants a comprehensive assessment of the long-term consequences of these trends and consideration of likely scenarios of climate change." As a result, we recommended that the Fish and Wildlife Program should, "Assess how climate-related changes in temperature and flow variability could affect natural production, habitat conditions, and likely ranges of species, which could reduce the effectiveness of Program measures and investments. Develop anticipatory approaches to evaluate options for adaptation to climate change."

This recommendation emerged because we deemed the Program's Climate Change Strategy too broad and found that it lacked specific direction, actions, and Performance Indicators. The ISAB further noted that while numerous projects within the Program acknowledge that changing climatic conditions will affect the project's performance, with some exceptions,[4] there has been limited structural attention to assessing climate risks and vulnerability where water uses, temperature profiles, and flow changes will impact species in different ways. The ISAB emphasized that Program actions and best-practices can benefit from robust forecasting of climate conditions and from selecting mitigation alternatives aimed at habitat and population resilience that accommodate those forecasted conditions. Our current review builds on our 2024 review of the Program to provide guidance on how the Program and its projects can better address climate resiliency.

1.4. Brief Overview of the Salmon Life Cycle and Environmental Influences

The life history of anadromous salmonids involves a series of phases in distinctly different environments (Figure 1). The causes, magnitude, and variation in mortality vary among these phases and environments. Each stage is affected by its physical and biotic environments and thus directly or indirectly by changes in climate on those environments. Here, we consider the life cycle to begin as the adults return from the ocean to spawn in natal streams and end with their feeding and growth at sea. Climate change produces sequential effects throughout the life cycles of populations in various ways. In particular, the timing of events in the life cycle (i.e., phenology[5]) is affected by climate change, given its dependence on temperature and streamflow.

The timing of adult upriver migration varies greatly among populations and reflects genetic adaptations to the long-term regimes of temperature and flow in the natal rivers that allow successful upstream migration to the breeding grounds (i.e., "ecological match"). For some populations, spawning occurs soon after returning adults arrive (e.g., fall Chinook salmon and winter steelhead), but others (e.g., spring Chinook salmon, sockeye salmon, and summer steelhead) have a long delay prior to spawning, and this largely reflects the physical conditions in the rivers (e.g., Brannon et al. 2004a, Quinn et al. 2016). Rapid alteration of conditions, such as increases in temperature, decreases in flow, or changes in salinity, can result in physiological stress and mortality during upriver migration (Naughton et al. 2005) and on the spawning grounds

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[4] A noteworthy exception highlighted in the ISAB report was the Lower Snake River Compensation Plan's climate vulnerability analysis to inform its spring Chinook production programs (see ISRP 2023-1).

[5] Phenology is the study of the timing and cyclical patterns of events in the natural world, particularly those related to the annual life cycles of plants, animals, and other living things. Critical applications of phenology include "assessment of the vulnerability of species, populations, and ecological communities to ongoing climate change." Source: National Phenology Network.

prior to egg deposition (e.g., Bowerman et al. 2018, 2021; Naughton et al. 2023). Such stress or mortality can have serious consequences for the populations. Thermal refuges (i.e., pockets or reaches with cold water habitats) provide some relief from high temperatures (Snyder et al. 2020) as documented for spring Chinook salmon (Berman and Quinn 1991, Torgersen et al. 1999) and summer steelhead (Baigún 2003, Baigún et al. 2000).

The timing of spawning is closely linked to the long-term average thermal regime of the stream so that developing embryos emerge at the optimal time to feed in the spring (Quinn 2018). Altered thermal regimes can result in mismatches between emergence and the production of food or the presence of predators, unless other aspects of the ecosystem shift synchronously. Further, while temperature plays the primary role in developmental rate, mortality is most strongly affected by scouring flows and the deposition of fine sediment into the egg pocket that often follows after the freshets peak (e.g., Johnson et al. 2025 and references therein). Thus, the combination of temperature and flow, both related to climate, play critical roles for developing embryos and pre-emergent juveniles.

Juvenile salmon and steelhead spend varying periods in streams (and lakes in some cases) prior to seaward migration. During this period, the temperature regime has a preeminent role in their activity, digestion, swimming performance, disease resistance, and other aspects of their lives with direct and indirect effects on growth, distribution, and survival. Similarly, many aspects of stream discharge affect feeding, distribution, movements, growth, and survival of juvenile salmonids in streams. Consequently, the effects of climate change and habitat restoration on flow and temperature regimes, including surface water and groundwater, depth, velocity, substrate and other features of the lotic environments, strongly influence juvenile salmon. For example, juvenile Chinook salmon grew faster in floodplains because hydraulic and temperature conditions produced more prey (Jeffres et al. 2008), illustrating the potential negative impacts of climate change and development that disconnect floodplains, and the importance of connected floodplains for mitigation.

After their species- and population-specific periods in streams, anadromous salmonids migrate to sea. The initiation of this migration is cued by photoperiod, but temperature also affects timing (e.g., Chinook salmon migrated earlier after warmer springs than after cooler springs; Roper and Scarnecchia 1999) or combinations of temperature and flow (e.g., Achord et al. 2007, Sykes et al. 2009). Thus, hydrosystem operations, development on the landscape, and climate change all contribute to alter the timing of peak temperature and stream flows across the Columbia Basin, hence juvenile salmon migrations.

In estuaries, where freshwater and marine ecosystems meet, salmonids experience the effects of climate-related processes, with temperature and flow again having the greatest effects, though these effects diminish as the effects of tidal forces and marine conditions grow in relative importance. Beyond the estuarine plume, physical conditions at sea, such as temperature, currents, upwelling, and chemistry, combine with biotic effects throughout the food web to affect salmon survival, growth, and maturity schedule.

Thus, throughout their lives, climate-driven changes in key physical and biotic factors have profound effects on salmonids. With respect to habitat protection and restoration projects, it is essential to 1) understand and forecast how local climate changes will affect the abiotic and biotic processes most important for the salmon's relevant life history stages, and 2) use field studies, experiments, models and other scientific methods to estimate how the restoration or protection project will function for fish under the likely climate scenarios.

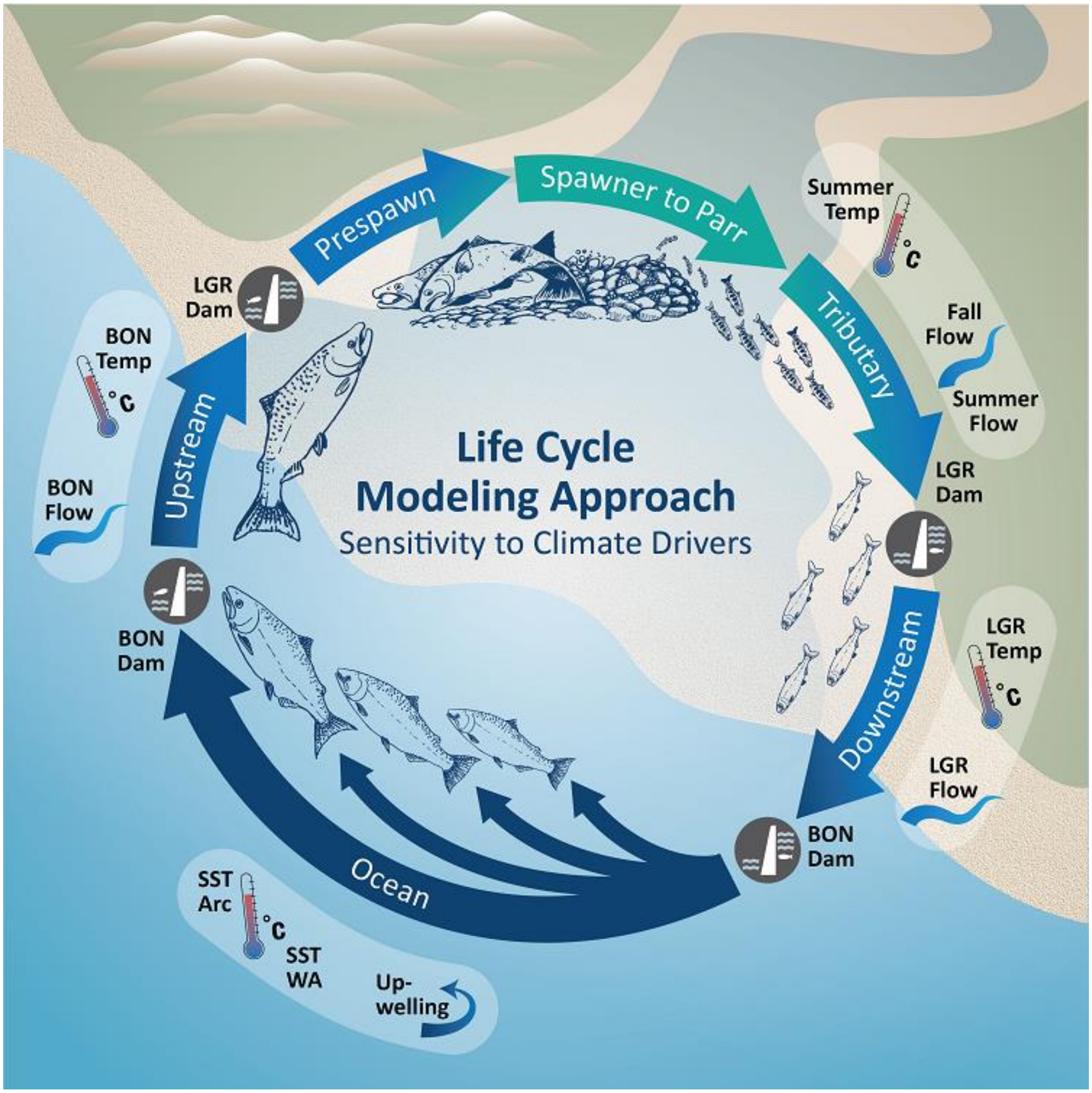

Figure 1. Diagram of salmon life cycle, showing life-stage transitions and the climatic covariates that affect each life stage (Source: Crozier et al. 2021, Figure 1). Abbreviations: temp = temperature, BON = Bonneville Dam, LGR = Lower Granite Dam (also see NOAA online article).

2. Climate-derived changes and associated challenges in the future Columbia River Basin

2.1. Evolving understanding of changing climate and its impact on fish and wildlife in the Columbia River Basin since the ISAB's 2007 Report

The Columbia River Basin ecosystem has experienced localized as well as basinwide modifications to the hydrology, land cover, and biotic communities for well over a century (Ebel et al. 1989; Figure 2). The productivity of anadromous salmon and steelhead, in particular, as focal species in this report, has diminished below levels typically needed for maintenance and replacement. These declines are especially acute and concerning for the recovery and restored viability of populations that are identified as imperiled.

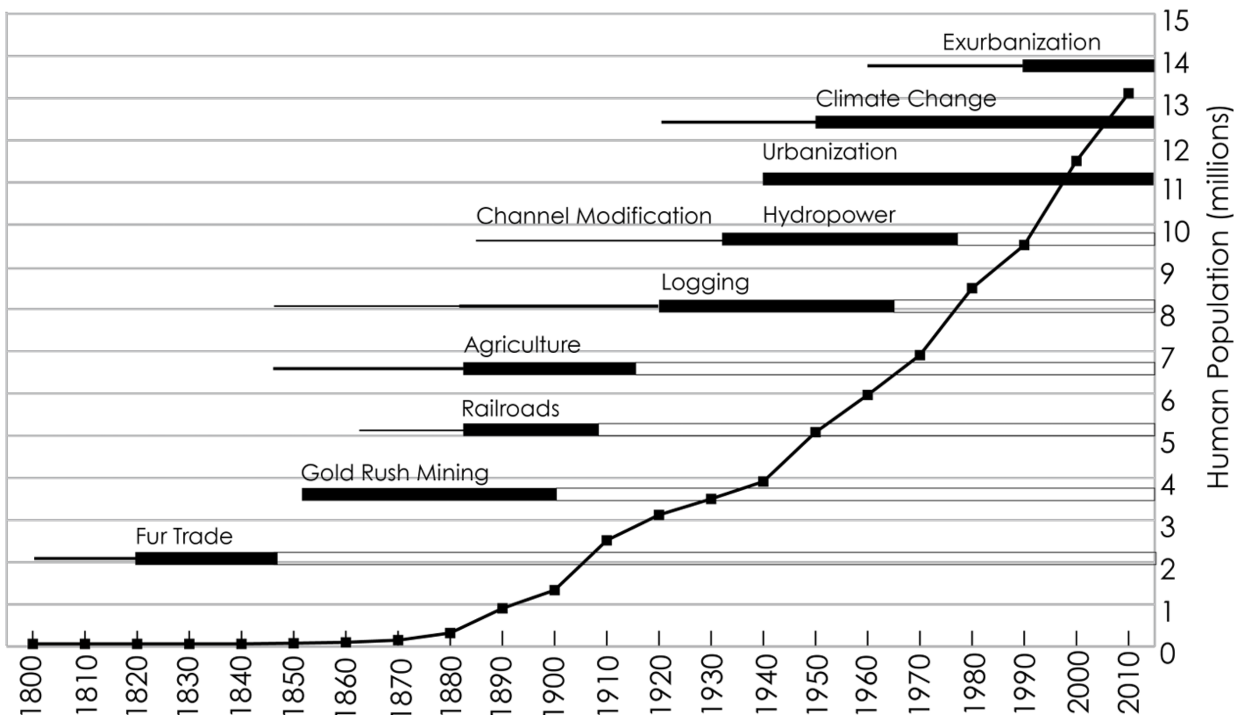

Figure 2. Primary anthropogenic factors driving landscape change in the U.S. portion of the Columbia River Basin, and concurrent changes in human population size. Wide dark bars indicate the period of peak effects and rapid habitat conversion caused by each factor. Wide light bars indicate continued effects following the initial period of rapid change (from ISAB 2011-4, Rieman et al. 2015, ISAB 2015-1).

The preponderance of scientific and management reporting has focused on anadromous salmon and steelhead within the Columbia River Basin (including within this report). However, we acknowledge that other fishes, as well as birds and terrestrial wildlife, have also been impacted by altered hydrology, human development and land-use practices, and harvest, among others.

The broad shifts in atmospheric and hydrologic conditions associated with changing climate that are forecasted within the basin are reasonably well understood (RMJOC 2018; presentations to ISAB from Crozier 2024 and Isaak 2025; NPCC 2014, FWP Appendix G; see also Quinn and Adams 1996 for historical context). These primarily include, but are not limited to, changes in temperature and streamflows. Ultimately, the observed conditions since at least 2007, and perhaps since the 1980s, underscore the rate and magnitude of temperature and streamflow changes over this short period (i.e., decades, not centuries).

Air and water temperature patterns. Since the ISAB 2007-2 report, the most evident shift in environmental conditions for the Pacific Northwest region and Columbia River Basin has been an increase in air temperature, consistent with global patterns (Figures 4 and 5). Although not uniform throughout the Columbia River Basin, mean air temperatures have warmed by more than 1°C since the 1970s (see Figure 3 for the global trend). This increase in air temperature has been accompanied by rising mean water temperature of ~ 1.0 to 1.5°C since the 1970s (Isaak 2025 presentation, slide 32; Isaak et al. 2018a).

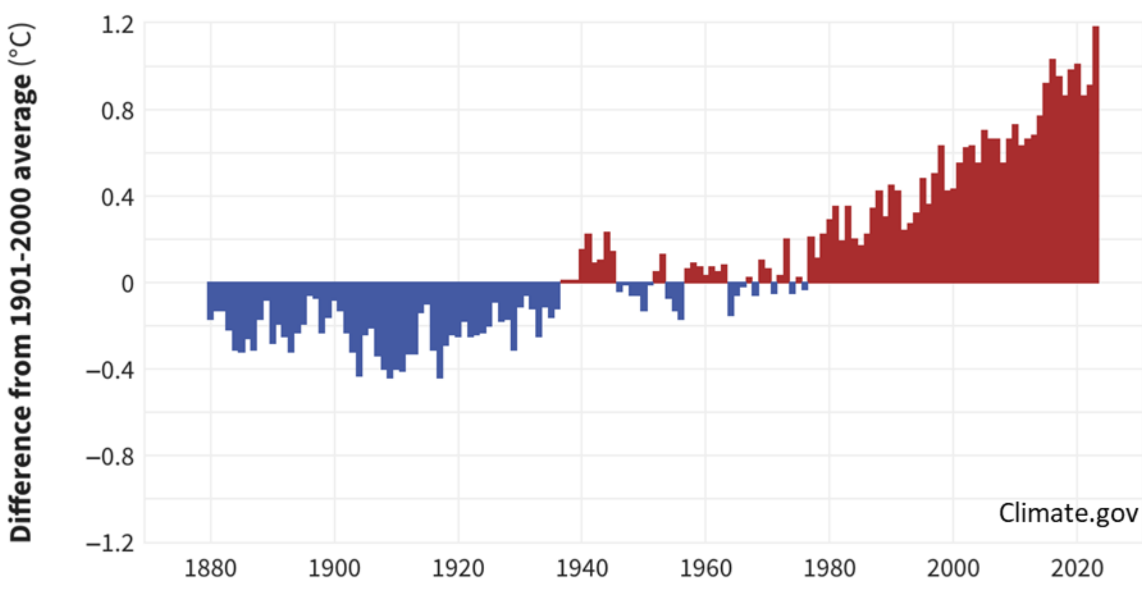

Figure 3. Pattern of increase to global average surface air temperatures (Source: climate.gov, cited by Mantua 2024 presentation, slide 3). Long-term, global average air surface temperatures reflect patterns also observed in the Columbia River Basin.

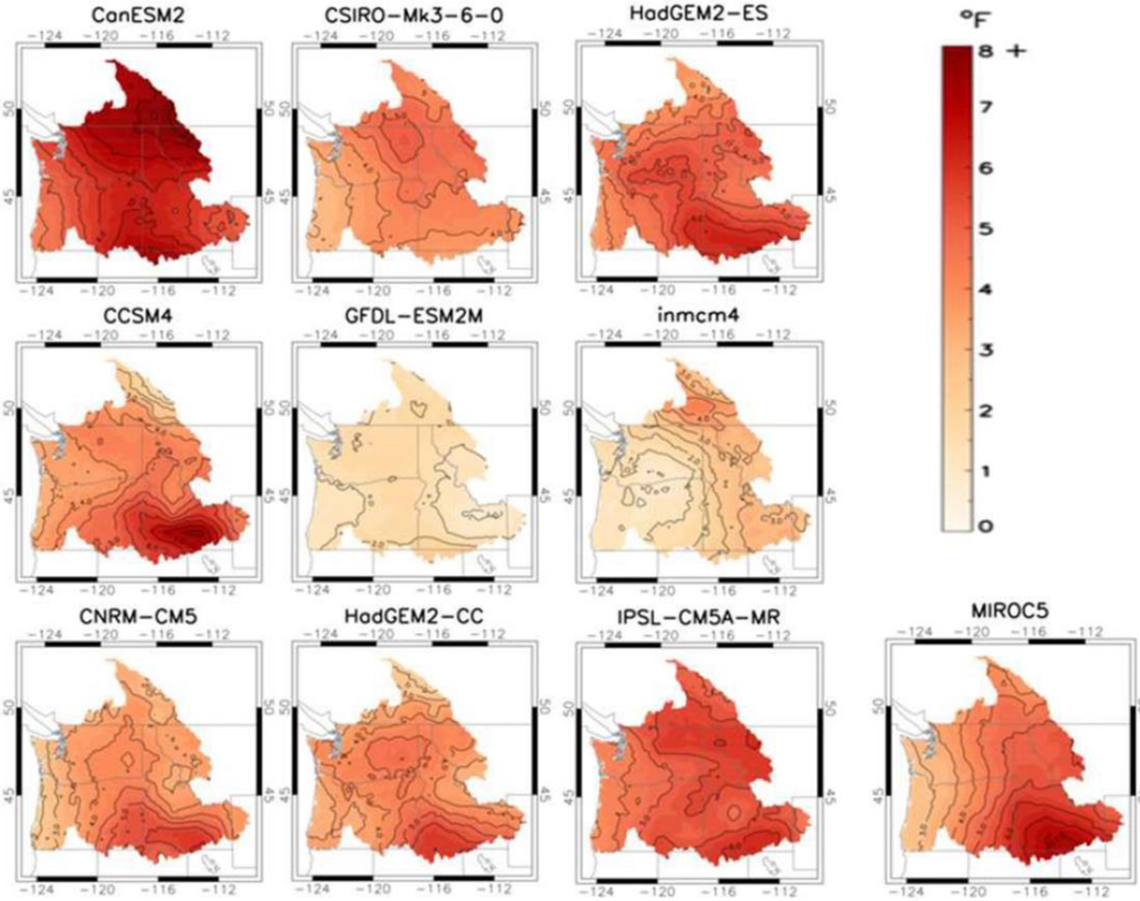

Figure 4. Predicted average winter temperature increases by the 2040s based on 10 climate scenarios for the Columbia River Basin. Source: Presentation by Daniel Hua to Council, October 1, 2024. Original source: David Rupp, Oregon State University. The figure demonstrates warming over most of the Northwest, especially in the interior relative to the coast, regardless of model examined.

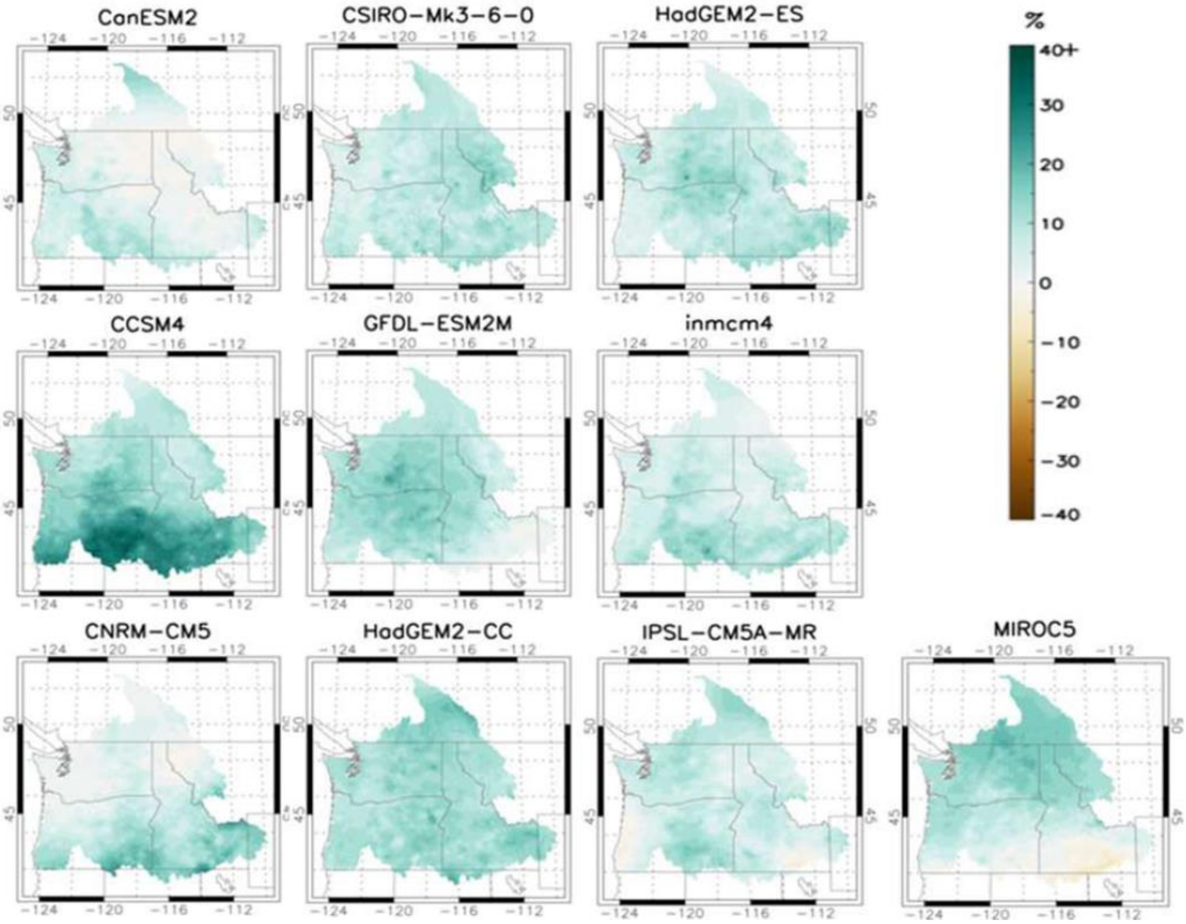

Figure 5. Predicted average winter precipitation increases by the 2040s based on 10 climate scenarios for the Columbia River Basin. Source: Presentation by Daniel Hua to Council, October 1, 2024. Original source: David Rupp, Oregon State University. The figure indicates increases in precipitation over much of the northwest, expected to fall primarily as rain rather than snow, increasing winter flows and reducing the snowpack over time.

Importantly, some years, such as 2015, experienced mean surface air temperatures well above both the projected mean and the associated variance (Figure 6; Mantua 2024, slide 5). Concurrently, 2015 also featured a marine sea surface temperature anomaly (the so-called, “heat blob”) in the coastal ocean adjacent to and north of the Columbia River outlet. Such an anomaly points to why both extreme events and ocean conditions are important for fish and wildlife practitioners to consider; climate change affects inland habitat conditions and also at sea, where much of the salmon life cycle occurs. The 2015 anomaly may foreshadow "average" mid-century conditions, which could be a useful point of reference in restoration and mitigation planning.

Looking forward, there are numerous model projections of future air and water temperatures. The range of modeled increases in air and water temperatures are driven by scenarios that account for global and local net greenhouse gas releases, sequestration, and accumulation. Further, predicted warming is unlikely to be uniform throughout the Columbia River Basin, with higher increases in the interior basin than in coastal areas. Nevertheless, a widely accepted pattern has emerged, with an additional 1°C (or greater) increase in mean annual surface air temperatures by the end of the present decade and of nearly 2-5°C over the next half-century (Figure 6).

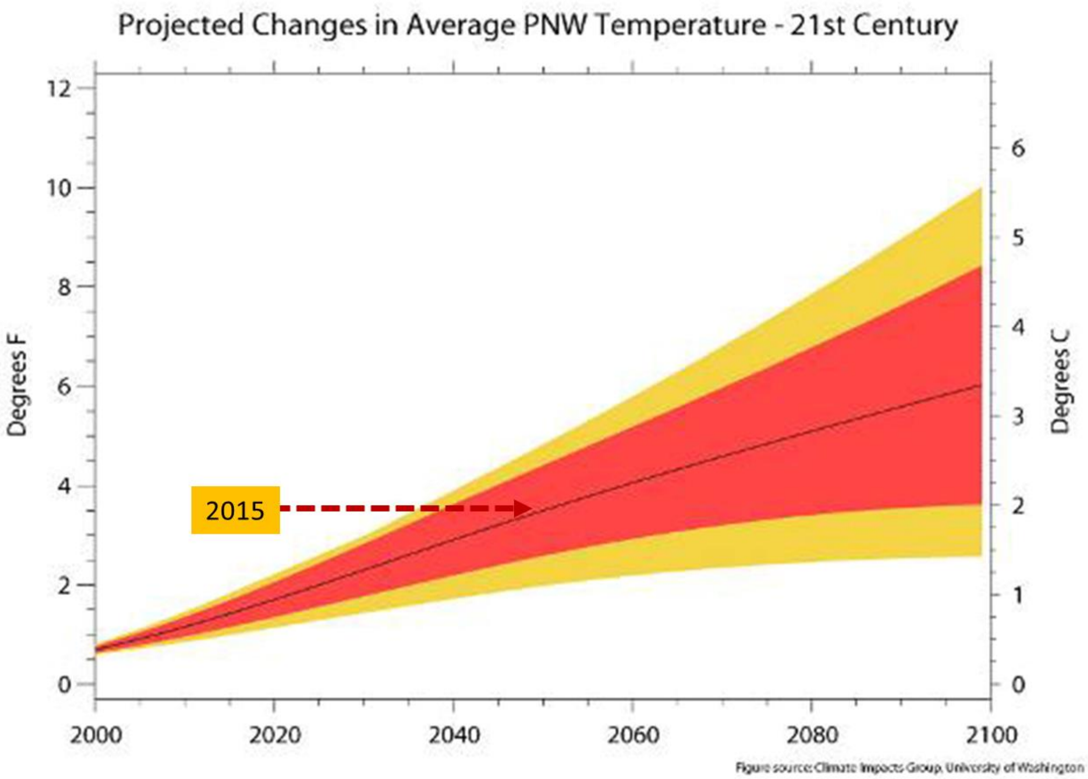

Figure 6. Observed versus projected trends in surface air temperatures for the Pacific Northwest since 2007 (Source: ISAB 2007-2, modified by Mantua 2024, slide 5). 2015 is highlighted as an extreme year for heat, with mean surface air temperatures well above both the projected mean and the associated variance for that year. However, it provided a preview of projected mid-century average temperatures (black line in the red shape).

Hydrological patterns and streamflow. Changes in temperature and precipitation will affect hydrology and streamflow patterns. Projected changes in precipitation include increasing annual precipitation, decreasing summer precipitation in western Oregon, and increasing precipitation in some winter storms (Salathe et al. 2010, Pierce and Cayan 2025). Forecasted changes in hydrology include increases in winter through early spring flows, an earlier spring freshet, and decreased late summer flows (RMJOC 2020, Chegwidden et al. 2020). Warmer winter temperatures are expected to increase the proportion of precipitation falling as rain rather than snow, reducing snowpacks. Inland glaciers that contribute to summer baseflows are also expected to continue their retreat (Moore et al. 2009). Slower and weaker westerly winds may contribute to reduced precipitation in the mountains (Luce et al. 2013).[6] Collectively, these hydrologic changes will likely result in an increase in average fall and winter flows (Queen et al. 2021), with precipitation and snowmelt-driven peak flows happening earlier in the year and the summer baseflow period becoming longer and lower.

Impacts of environmental changes on salmonids. Since the previous ISAB report (2007-2), research and monitoring have provided a much more detailed and nuanced understanding of the impacts of climate change on salmon in the Pacific Northwest. Since 2007, a database of published works maintained by NOAA Fisheries (AMIP 2010-20; Crozier et al. 2008a, b, 2020, 2021; Crozier 2024 presentation, slide 3) contains more than 1800 individual publications examining climate effects on salmonids. Crozier and Siegel (2023) reviewed this database, and several themes emerge from this and other reviews. First, climate change interacts broadly with salmon species over their life cycles. Second, most publications focused on the freshwater components of life history, although this research focus does not mean that effects at sea are unimportant or not occurring. Third, the climate-driven changes (e.g., earlier onset of spring conditions, warmer summer, and later fall) are reflected in a mix of phenotypically plastic responses and pressures from natural selection on traits with stronger genetic control. For example, migration and spawning timing are largely under genetic control, and warming conditions may selectively cull salmon that migrate or spawn when conditions are unfavorable. This may result in a gradual change in timing. On the other hand, incubation rate is largely controlled by temperature, so fry will emerge earlier under warmer conditions and this response to altered temperatures will be immediate. Early emergence allows a longer growing season and may shift the duration of rearing in streams prior to smolt transformation and affect smolt timing. These changes can lead to "carryover" effects, where growth or timing at one stage affects fitness-related traits at one or more subsequent stages. The general principles of selection and plasticity are well-understood and thoroughly studied in salmonids, but uncertainties remain regarding the interactions among accelerated embryonic development schedules, fry behavior, diet and food availability, predator abundance, and other factors that may affect population-level viability of salmon. Notably, changing temperature, hydrological, and other environmental

[6] Uncertainties about wind projections are discussed on pages 14-20 in the sixth Oregon climate assessment (Fleishman ed. 2023).

conditions have been observed throughout the Columbia River Basin, but salmon species and populations differ in their responses (Mantua 2024 presentation, slide 14).

Plastic versus evolutionary response mechanisms. Over shorter time frames, phenotypic plasticity (or flexibility) in physiology and timing may buffer populations from the effects of climate change up to a point. Over longer time frames, however, fish populations may adapt genetically to better match the new abiotic conditions, may shift their ranges, or may suffer demographic consequences and even become locally extirpated. As a result, the exact effects of climate change stressors on fish and their responses at short and longer time scales are complex and uncertain. Potential responses of Pacific salmon to climate change throughout their life cycle were explored by Crozier et al. (2008a). Low heritability but relatively quick plastic responses (e.g., emergence time, smolt migration time, habitat choice) combined with high heritability evolutionary responses through selection (e.g., upstream migration date, spawning date) will likely combine to determine productivity and persistence of salmon as features of climate change combine with other stressors.

Extreme events on salmon populations. Nathan Mantua's briefing to the ISAB (2024) emphasized the role of climate extremes in the expected nonlinear decline of species. A series of extreme years may ultimately lead to the extirpation of certain populations, rather than a more uniform and gradual decline. For example, during heatwaves, such as the one experienced in 2015, a large percentage of ocean-phase salmon were exposed to very high temperatures (>21°C), causing thermal stress, migration delays, and pre-spawn mortality (Bowerman et al. 2018, 2021; Snyder et al. 2020; Naughton et al. 2023; Mantua 2024 presentation, slide 6). These events were foreshadowed by high temperatures and effects on salmon decades ago (e.g., Major and Mighell 1967).

Wildfires, fish, and climate. The ecological consequences of wildfire for aquatic species, and salmonids in particular, have long concerned resource managers and stakeholders across western North America (Gresswell 1999). These concerns have been heightened in recent decades by two factors. First, a century-long "fire deficit" caused by pervasive fire suppression has led to overall increases in fuel loads and tree densities and has contributed to a growing prevalence of large, high-severity (stand-replacing) fires in forested landscapes (Parks et al. 2025). Second, it is likely that changing climatic conditions will exacerbate this trend (Westerling et al. 2006, Halofsky et al. 2020). Although even low- or moderate-severity fire can affect aquatic ecosystems, high-severity fires tend to have the most pronounced effects (Erdozain et al. 2024). These include a heightened potential for blackwater events and debris torrents caused by high-intensity rainfall on hydrophobic soils during a burn (Curtis et al. 2025) or the first few years after

(Cannon et al. 2010). These events are characterized by temporary but extreme degradation of water quality—anoxia and spikes in turbidity—and sometimes wholesale rearrangement of streams channels, a combination that frequently leads to local or extensive fish kills (Brown et al. 2001, Bozek and Young 1994, Curtis et al. 2025). The loss of riparian vegetation (and thus shading) also leads to an increase in water temperature (Minshall et al. 1997, Mahlum et al. 2011, Warren et al. 2022) that persists until the forest overstory regrows, a process that may require decades. Consequently, the general perception is that wildfire has a negative and lasting effect on the aquatic biota in stream ecosystems (Dunham et al. 2003, Roon et al. 2025).

The response of salmonids to post-fire environments, however, suggests a different interpretation. In many instances, changes in fish populations appear to be limited (Dunham et al. 2007, Koetsier et al. 2007, Swartz and Warren 2022, Preston et al. 2023). In these instances, even though isolated and relatively small fish populations can be extirpated by extreme post-fire changes (Cooper et al. 2015), demographic connectivity to upstream or downstream locations unaffected by fire (including migratory individuals elsewhere in a basin or at sea) generally provides an adjacent source of individuals for recolonization (Bisson et al. 2003). Generally, salmonid populations in severely burned watersheds rapidly rebound from initial declines, with substantial increases in recruitment or growth rate 1–10 years following fire (Burton 2005, Howell 2006, Sestrich et al. 2011, Rust et al. 2019). These responses are thought to result from greater primary production (from increasing light and warmer temperatures) driving increases in aquatic macroinvertebrate availability (Minshall et al. 1997, Silins et al. 2014, Swartz and Warren 2022), but the mechanisms remain uncertain. Longer-term changes in salmonid populations in post-fire landscapes remain largely unexamined, but the fire-related bulk contributions of sediment and large wood are thought to promote stream habitat complexity that can contribute to salmonid population persistence almost indefinitely (Bisson et al. 2009).

Although the evolutionary history of salmonids suggests that they have adapted to fire-related disturbance in the Pacific Northwest, one aspect of climate change may alter that relationship: an increase in fire severity or frequency that leads to conversion of forested landscapes to those dominated by shrublands or grasslands (Coop et al. 2020, Hoecker et al. 2023). Simulation studies imply that type of conversion may become relatively common, which would dramatically change flow and thermal regimes, reduce the structural contributions of dead trees to channel morphology, and reorder food webs based on trees to those involving shrubs and grasses.

Building on previous ISAB reporting. Some of the thermal, streamflow, and ecological changes were detailed in the ISAB's 2007 report (ISAB 2007-2) that listed 28 key findings and 11 recommendations for the Columbia River Basin Fish and Wildlife Program. Some of those key findings and recommendations from the ISAB's 2007 report that are especially relevant to this present effort are summarized below with a brief update of status:

- Climate change, in combination with expansion of human populations, will reduce and fragment wildlife habitats and can affect most freshwater life history stages of trout and salmon. This finding remains relevant, though our understanding of climate extremes, including marine heat waves and changes in PDO and El Niño/La Niña cycles, have matured. Further, scientists and managers now have access to data and models to examine the extent of changes expected in the Columbia River Basin and to species and life stages.
- We must be prepared to accommodate major surprises (Root and Schneider 2002) and plan for a high degree of uncertainty rather than a narrower solution that might appear optimal today. The significant scientific advancements since 2007 have reduced uncertainty across geographical areas and watersheds. However, a focus on dynamic and diverse ecosystems is still relevant today as a primary mechanism for ecosystem resilience and adapting to changing conditions.
- Changing climate affects aquatic and terrestrial species, and the entire composition, structure, relationships, and function of the ecosystem. Therefore, to solely focus on selected species of high economic value or conservation focus without considering the underlying and supporting components of the ecosystem will limit the chances for long-term viability and ecological resilience. Further, climate-related changes are exacerbated by human population growth and land use changes along river and tributary corridors. This finding, emphasizing the need to expand considerations beyond particular species and environmental changes, still stands.
- Integration of climate change planning into mitigation and restoration within the basin has been hampered by several factors, including the availability of climate change projections at spatial resolutions and in formats that can readily be used at scales relevant to project implementation. Fortunately, this limitation has been largely addressed by federal, Tribal, academic, and NGO entities, for example, the NorWeST stream temperature database, USGS Climate Adaptation Centers, and the River Management Joint Operating Committee (RMJOC).
- Mitigation priorities in the ISAB 2007-2 report focused on approaches addressing hydrology and temperature such as flow augmentation and cold water refuges. Recommended actions included flow augmentation with cool/cold water storage reservoirs, surface weirs to reduce juvenile occupancy times in dam forebays, cold water

augmentation in ladders, focusing fall transportation based on temperature and developmental stages, transporting returning adults around lethal temperature conditions of the lower Snake River, expanding predator control of non-native piscivorous species, and opening of backwater and off-channel habitats as possible cold water refuges. The report also recommended assessing the options for accommodating climate changes into harvest management planning, including restrictions on impacted stocks to allow recovery. While these practices are still important mitigation tools, comprehensive frameworks to prioritize and plan where and when to apply them are incomplete.

2.2. Headwaters to Large Tributaries

The 2007 report acknowledged that intensity of responses will vary spatially but were expected to impact "virtually all tributary systems" in the Columbia River Basin. In the key themes below, we summarize different aspects of climate change impacts across the full Columbia River Basin draining to the mainstem Columbia River.

Temperature effects on fish growth and life history pathways. Modeling by Beer and Anderson (2010) combined temperature changes and bioenergetic models showing that impacts of climate change on juvenile anadromous salmonids will likely vary across ecoregions within the Columbia River Basin. They found that: "Increasing mean temperature increases juvenile growth in streams that currently experience cool spring temperatures. In streams with currently warm spring temperatures, an increase shortens the duration of optimal conditions and truncates growth. A loss of snow enhances growth in cool summer streams and decreases growth in warm-summer streams." Increased growth may be considered a positive effect if it leads to larger smolts with higher survival, but it can increase residualism (i.e., non-migratory behavior) and thus decrease life history diversity in steelhead (Benjamin et al. 2013). This reduction in diversity may also occur in non-anadromous cutthroat trout and bull trout (Isaak and Young 2023) and may be particularly problematic for bull trout populations dominated by migratory fish (Kovach et al. 2018).

Salmonid occupancy in and importance of cold headwater streams. For small stream reaches (e.g., third-order or smaller channels), advances in modeling have helped define and predict the climate effects on small stream salmonids. However, anadromous species, including salmonids and Pacific lamprey, are less likely to broadly occupy these habitats (Young et al. 2022a). Rather, the native components of these fish communities tend to be species-poor, consisting of westslope cutthroat trout *O. lewisi* in the interior, coastal cutthroat trout *O. clarkii* nearer the coast, or rainbow trout (Young et al. 2016), one or two sculpin species (Young et al. 2022b), and in very cold systems (mean August temperature < 11 °C), bull trout (Isaak et al. 2015, Benjamin et al. 2016). Moreover, even for these salmonids, the estimates of occupied habitat are generally lower than previously assumed or predicted. In most cases this was not because of recent declines (Isaak and Young 2023; but see Lemoine et al. 2020) but because habitat occupancy in small streams has been exaggerated (Isaak et al. 2025). Many portions of first- and second-order channels are either too steep (>15% gradient) to be suitable, or the steep portions contain migration barriers that prevent occupancy of upstream portions of these basins. In addition, very small channels (<0.2 ft^3/s) may be more subject to intermittency, too small to provide the essential habitats for long-term persistence, and often too cold in headwater areas (Penaluna et al. 2022, 2023; Isaak and Young 2023).

Small streams, whether occupied or not, are critical for sustaining salmonid populations throughout the Columbia River Basin because they deliver cold water and food downstream (ISAB 2011-1). Over the last decade, there has been an emerging appreciation of these cold-water reaches as climate refuges providing natal or life-long habitats for some species (Isaak et al. 2015, Isaak and Young 2023) and that tributary junctions provide surface or hyporheic plumes of cold water thermal refuges in larger-order streams and rivers (Sullivan et al. 2021; see Section 3.3, Approach 2). They also represent the locations where some strategies are likely to be most effective, such as restoring riparian shade (Fuller et al. 2022). Small streams at higher elevation may be warming less rapidly than lower-elevation systems (Isaak et al. 2016, Isaak and Luce 2023). This greater level of thermal inertia suggests that these stream reaches may constitute a vital network of climate refuges worth preserving that can persist throughout much of the 21st century (Isaak and Young 2023). However, small mountain streams are expected to decline in discharge (Isaak and Luce 2023), which may reduce their suitability or accessibility, and their thermal influence on larger, downstream channels.

The importance of thermal refuges along the mainstem and large tributaries. The ISAB (2007-2) report recognized the importance of thermal refuges to salmon and steelhead in the Columbia River Basin. Availability of cold water to adult spring Chinook salmon and summer steelhead is especially important during their upstream migration in the hottest months. A significant scientific effort has been expended since the ISAB (2007-2) report to locate cold water refuges (Palmer 2017) and to understand their role in salmon and steelhead survival and production in the Columbia River Basin (Snyder et al. 2020, Siegal et al. 2021). Protecting existing thermal refuges (Mejia et al. 2023) and managing for their persistence where most needed (Isaak and Young 2023) as the climate changes are continuing challenges.

Disruption of local adaptation. Crozier et al. (2008a) posited that some responses to climate change may erode distinctive life history traits due to gene flow with co-occurring populations. For example, fall Chinook salmon in the Snake River may find lower elevation spawning areas less attractive or unusable because of temperature and sedimentation changes, and if they shift their spawning distribution upstream, they might interbreed with populations of spring Chinook salmon. If this occurred, it could lead to the loss of locally adapted traits. The shrinking of spawning habitat to higher elevations could also result in interbreeding between hatchery-origin and wild stocks.

Mismatched timing of ecological life cycles. The timing of spawning, fry emergence, and seaward migration of salmon smolts has evolved around a suite of environmental conditions. As noted in many studies, climate change can be an evolutionary force of natural selection on timing. For example, Austin et al. (2021) reported that wild populations of Chinook salmon responded to a warming river by spawning later in the year in the Skagit River system. However, inadvertent selection in the local hatchery for earlier spawning caused that population to spawn earlier, clashing with the effects of climate change. In another example, Wilson et al. (2021) reported that survival of steelhead smolts from the Wind River depended on the matching of early ocean conditions with population traits of size and river exit date, which varied with freshwater growing conditions. This research is consistent with other studies indicating that timing of ocean entry is more important than smolt size, and that date and size co-vary (reviewed in Quinn 2018). To the extent that climate change (i.e., river flow and temperature regimes) stimulates salmon to migrate at ecologically suboptimal dates and affects their size, the survival of smolts at sea can be altered. These processes are complicated, and the timing of key life history events should be documented and the possible effects incorporated into management actions.

Interacting effects of climate change and habitat stressors. Climate change is expected to intensify the negative effect on salmonids where riparian loss has already occurred associated with development of land, such as for agriculture, as modeling by Wooster et al. (2019) found in the Umatilla subbasin for steelhead. Habitat modeling showed that the incubation and spawning adult life cycle stages would likely be most affected by seasonal temperature increases. Effects of climate change are not affecting all areas similarly. Wade et al. (2013) reported that sensitivity of steelhead will likely vary across the Pacific Northwest, with greatest increases in temperature in the southern areas and greatest changes in flow in the interior and northern Pacific Northwest. Based on their modeling of habitat conditions, steelhead would be the most sensitive to climate change in the west Cascade and southern coastal regions.

However, it is important to consider that the growth of juvenile salmonids (and other fishes) is largely controlled by the interaction between food and temperature. Given unlimited food, growth is maximized at species- and population-specific temperatures. Thus, if temperatures are sub-optimal, warmer water can accelerate growth, but if temperatures are already optimal or above, further increases will reduce growth. For example, Lusardi et al. (2020) found that adequate food resources could mitigate the negative effects of increased water temperatures on juvenile coho salmon expected from climate change, and increased growth of juvenile salmonids after removal of riparian cover have also been reported (e.g., Holtby 1988).

2.3. Mainstem

Regarding climate effects on the mainstem, the ISAB (2007-2) observed that condition changes to the mainstem and basin from hydrosystem development, along with land-use and water-use changes, had already altered the ecosystem relative to historical river conditions prior to the climate changes in the late 20th and early 21st centuries (e.g., Quinn and Adams 1996, Quinn et al. 1997, see review by Ebel et al. 1989). These changes reduced summer flows and increased winter flows relative to the unmanaged regime by seasonal water storage and release patterns. These patterns are expected to intensify as the climate warms and the hydrosystem transitions to a more rain-dominated hydrology over snow-dominated winter conditions.

Since the 2007 report, much effort has been undertaken to examine the impacts of climate change on the main channel and on anadromous fish, as summarized by Beechie's briefing to the ISAB (Beechie 2025). Each species and run extends across multiple seasons, years, and locations across its life cycle, and therefore experiences multiple climate-related changes in water temperature and flow. These changes can be stressful and interact with other stressors associated with habitat changes from the hydrosystem and other human activities. These impacts on specific features of the anadromous fish life cycle vary among the species and can have cumulative effects on survival (Beechie et al. 2023b). Some of these impacts are similar to those described in the "Headwaters to Large Tributaries" section above, whereas others are unique to the mainstem.

Enhanced predation and resource limitation by non-native species. Changes to the assemblage of aquatic species are expected as a result of introduction and expansion of non-native, warm- and cool-water species such as American shad, smallmouth bass, northern pike and walleye that might compete with or prey on juvenile salmon. Such changes occur throughout the Columbia River Basin where altered temperature regimes and other habitat conditions favor non-native species. The combination of warming water temperatures and the prevalence of non-native species such as smallmouth bass and northern pike has been described by Jan et al. (2025) as "double trouble" for native redband trout and bull trout in the Columbia River Basin. Increased niche overlap between native and non-native species would likely increase the negative effects on native species from direct effects such as predation and subtler changes in behavior and physiology that increase salmon vulnerability (e.g., Kuehne et al. 2012).

Exposure, sensitivity, and adaptive capacity to climate change: The vulnerability of anadromous fish to climate impacts across the salmon life cycles was further addressed by Beechie et al. (2023b, and references therein). The authors describe vulnerability with three components (exposure, sensitivity, and adaptive capacity). Using life cycle models to examine exposure to a detrimental condition (i.e., the likelihood of a population experiencing that detrimental condition), such as elevated temperature or extreme hydrological condition, can be used to predict the impact to that condition (Fogel et al. 2022). How the population might respond to exposure depends on its biology and how it is managed. Thus, as seasonal and annual mean temperatures increase, more vulnerable species or runs (such as spring Chinook salmon, because adults hold throughout the warmest period of the summer in freshwater prior to spawning, and typically their offspring are stream-type, spending a whole year in streams prior to seaward migration), will experience the most severe declines without some action to ameliorate the thermal shifts.

Thermal refuges at tributary confluences: A critical element of the Lower and Mid-Columbia River's resilience through provision of thermal refuge at tributary junctions, but they have been substantially modified and thus are not providing the needed refuge. For example, W. Sharp and C. Seaton (2025) briefed the ISAB on the role of deltas at the confluence of smaller tributaries such as the Wind, White Salmon, and Klickitat rivers with the Columbia mainstem. Currently, these shallow and exposed deltas are potentially hazardous for juvenile salmon because of high temperatures and exposure to predatory birds. However, these deltas and associated plumes could provide thermal refuges if they were altered to offer deep pools of cool water. Many historical stream mouths and deltas are now flooded with backwaters from dams (e.g., Tucannon River, John Day River, Wind River) and their value as habitats for juvenile salmonids is altered by introduced aquatic plants such as Eurasian water milfoil (Kusnierz and Tholl 2024) and elodea (Carey et al. 2023). Assessments of the use of these deltas by anadromous fish, their predators (both fish and birds), and non-native competing species are greatly needed.

Considerable concern has been raised about climate change's role in the warming of lower reaches of tributaries and the mainstem rivers. Warm water can induce steelhead to migrate upstream of their natal rivers (Richins and Skalski 2017). Such "overshoot" of natal tributaries can result in a failure to return to the natal location. This homing failure can result in hatchery-origin fish breeding with wild fish and loss of wild fish from their natal populations. There is further evidence that moderate (i.e., non-lethal) temperature differences between mainstem and tributaries affect straying, as salmon (e.g., spring Chinook salmon) tend to avoid higher temperatures (Westley et al. 2025).

In sockeye salmon, there is a long history of research on the ways in which warm water can delay migration (Hyatt et al. 2003, and references therein). In extreme conditions, elevated water temperatures can result in large en route mortality of sockeye salmon (i.e., prior to reaching the spawning grounds). These losses have been extensively studied in the Fraser River system (Hinch et al. 2012 and references therein). In the historic hot summer of 2015, only about half of the adult sockeye salmon counted at Bonneville Dam were counted at Rock Island Dam (510,706 vs. 264,678, from DART), the last dam passed by the sockeye destined for the Okanagan and Wenatchee systems, which dominate the total counts in the river basin (Harrison 2015). The Columbia River Basin is the southern edge of sockeye salmon distribution, so the impact of climate change will likely be especially severe for this species (Hyatt et al. 2003, Isaak and Young 2023). We note that these kinds of effects of high temperatures on sockeye salmon were reported many decades ago (e.g., Major and Mighell 1967), so we are now seeing the exaggerated manifestation of a long-standing pattern.

Migration and dispersal corridor: The mainstem Columbia River not only serves as habitat and a migration corridor for juvenile and adult salmon but as a dispersal corridor for introduced plants, fish, and other organisms. The extent to which introductions take hold and prosper will rely on conditions at the source and its connectivity to upstream or downstream suitable habitat (see Tullos et al. 2016). Climate change can deter or facilitate these introductions, depending on antecedent habitat requirements.

2.4. Estuary

Vital Transition Zones: Estuaries are important transition zones for downstream migrating juvenile salmonids and adults migrating upstream to spawn. Fresh et al. (2005) concluded the Columbia estuary was particularly important for salmonids that enter the estuary as fry, fingerlings, or sub-yearlings, including ocean-type Chinook, chum, and pink salmon, and some coho salmon. Bottom et al. (2005) identified that a lack of information on Columbia estuary use by salmon hindered the implementation of appropriate restorative measures; the same was true for the ISAB (2007-2). Fortunately, more recent studies specifically focusing on the lower Columbia River and estuary have improved our current understanding. For example, Weitkamp et al. (2012) found that coho, sockeye, chum and yearling Chinook in the Columbia estuary were most abundant in May whereas subyearling Chinook were most abundant in late June. Crozier et al. (2021) reported that the marine life stage, including the estuary, was the most vulnerable to warming for spring/summer Chinook salmon in the Snake River.

In contrast to the extensive research on the use of the estuary by juvenile salmonids, studies on movements of adults in the Columbia River estuary have been very limited. Olson and Quinn

(1993) tracked individual fall Chinook in the lower river and estuary with sonic transmitters and reported the depth distributions of the fish, relative to available temperature and salinity levels. Other than this study, over three decades ago, the vertical and horizontal movements, use of shorelines and open water, natural and modified habitats, and other important considerations for adult salmon in the estuary are largely undocumented. These behavior patterns will vary among species and populations with run timing and other attributes, and so the need for research in this area is great.

Climate Related Physical and Biological Changes: ISAB (2007-2) noted that estuarine climate change effects on salmonids were generally not well understood due to the complexity of estuarine transition zones. Nevertheless, that report provides many relevant examples, of which only a few are repeated here. First is that sea level rise combined with increased winter flows may degrade or alter estuarine fish habitats due to sediment deposition from increased wave damage during storms. In addition, fish species adapted to warm water, including several non-native species, may benefit from future increases in temperature and changing food webs; the effects of these changes on salmonids and other native fishes are unclear (Sol et al. 2021). As well, the combination of climate change reductions in early summer river discharge and reductions related to flow management for hydroelectric power production, could allow the saltwater wedge to extend further upstream, potentially affecting harpacticoid copepods and other prey for young salmon and other fish. Finally, earlier snowmelt resulting in higher spring freshets, combined with warmer temperatures may cause spring Chinook and steelhead yearlings to smolt and emigrate to the estuary and ocean earlier, potentially resulting in mismatches between their arrival timing and coastal upwelling, reducing marine survival (ISAB 2007-2). On the other hand, such changes might benefit the salmon by partially offsetting the delays in travel time associated with the dams and reservoirs. In short, there are many important uncertainties regarding climate effects on salmonid ecology in the Columbia River estuary.

Climate Uncertainties and Concerns: Since 2007, progress has been made to address some of the uncertainties and challenges outlined in ISAB (2007-2). For instance, programs now provide some data and data summaries relevant to the effects of rising sea levels in the lower estuary. For example, physical parameters (e.g., salinity, temperature, water levels, velocities, turbidity, dissolved oxygen) of the estuary are being monitored and modeled (including future conditions) through the Coastal Margin Observation and Prediction (CMOP) program, operated by CRITFC in the Lower Columbia River estuary.

It is unclear whether storm surges and king tide patterns leading to saltwater intrusion and erosion are changing. Further observations and analysis of juvenile salmon and steelhead migration and habitat use in the estuary, as associated with changing hydrologic and thermal features from upriver, would be informative (e.g., Harnish et al. 2012). In comparison, much more work on flow, migration routes and survival of Chinook salmon has been conducted in the Sacramento River system (e.g., Michel et al. 2013, Perry et al. 2018). These changing features may lead to potential mismatches of food availability and presence of predators, especially birds (e.g., Collis et al. 2024). That is, changing hydrological and thermal patterns may result in juvenile salmon and steelhead migrating to and inhabiting the estuary at a time when their food is not as available, but predators are highly abundant. Thus, the value of long-term trend data documenting climate-induced changes in tidal patterns and saltwater intrusions, and their impact on salmon and other species, cannot be understated. Finally, as noted above, the dearth of information on adult salmon use of the estuary is striking, even compared to the many uncertainties regarding juveniles. Exposure to fisheries and predation from marine mammals in the estuary is very extensive, so the behavior patterns (e.g., travel rates and routes) of species and runs can greatly affect return to upriver areas.

2.5. Ocean

Climate Related Physical and Biological Changes: ISAB (2007-2) also addressed the ocean in some detail, and readers are encouraged to review that document. In brief, physical changes in the ocean associated with climate change include warmer waters, increased stratification of the water column, and variation in the intensity and timing of coastal upwelling that affect temperature, food production, competitors and predators. A lack of certainty in future climate patterns means we have little confidence in projections of changes to salmon habitat in the northeast Pacific Ocean. In the context of this current report, the ISAB notes that oceanic conditions strongly influence salmon abundance and productivity. While most opportunities for improving salmon resilience occur during freshwater phases of their life cycle (as noted in ISAB 2025-1), it is a mistake to assume that nothing can be done to affect what occurs in the ocean.

About four decades ago there was a growing awareness that ocean conditions (e.g., upwelling in the California Current Ecosystem) affected salmon survival (e.g., Mathews 1980, Scarnecchia 1981, Nickelson 1986). Similarly, evidence was reported that the growth of salmon at sea was affected, in part, by density and thus competition could be an important factor (e.g., Mathews 1980, Rogers 1980). The exceptional magnitude of the 1982 – 1983 El Niño event and the sharp decreases in salmon growth and survival (e.g., Johnson 1988) gave the scientific community greater appreciation for the importance of the links between the atmosphere and oceanic conditions affecting salmon (reviewed by Pearcy 1992). It soon became apparent that around the year 1977 a series of altered atmospheric events linked to the Northeast Pacific Ocean dramatically affected salmon and other marine fishes. The effects tended to be anti-correlated between northern and southern regions with increases in abundance and survival among northern populations (e.g., Alaska) and decreases among southern populations (Francis and Sibley 1991, reviewed by Quinn 2018). Studies revealed the association between different ocean-atmosphere indices and performance of salmon and other marine organisms on inter-decadal scales (e.g., Beamish 1993, Beamish and Bouillon 1993, Mantua et al. 1997). These natural oscillations in physical conditions, with strong but incompletely understood linkages to the biota, increasingly interact with climate changes driven by human use of fossil fuels.

In the ocean, as the climate changes, we can expect further changes in primary and secondary productivity that alter marine ecosystems and affect the growth, productivity, survival, and migrations of Columbia Basin salmonids. Caloric requirements increase with warmer waters, which will require increased prey consumption to maintain growth that may only sometimes be compensated for by improved growth and survival. Anticipated increased ocean acidity will negatively impact various organisms including pteropods, an important food source for some salmon.

The result of atmospheric warming has not been limited to simple increases in average sea surface temperatures but rather, extremely warm years at some locations, with highly variable physical conditions overall (e.g., Laufkötter et al. 2020). During 2013-2023, warming in the North Pacific was significantly greater than in other ocean basins (Hu et al. 2024). In winter 2013-14, extreme warm temperature anomalies developed under the influence of a persistent high-pressure anomaly in the Northeast Pacific and that became known less formally as “the warm blob” (Bond et al. 2015). This anomaly, ~500 km wide and ~100 m deep, persisted until 2015, resulting in an unprecedented toxic algal bloom and major changes to the zooplankton community (McCabe et al. 2016). As reported by Homel and Bach (2024, pg. 65): “As the blob eventually moved onto shore, productivity in the nearshore environment also plummeted and numerous marine species were negatively affected. This widespread low productivity resulted in extremely poor ocean survival rates of Columbia Basin salmon and steelhead. Additional marine heatwaves occurred in 2019, 2020, and 2021. During 2015, at the height of the blob, water temperatures in the Columbia River exceeded 70° F at the time that sockeye salmon were migrating upstream. Over 250,000 sockeye salmon died during migration before they could reach their spawning grounds.”

Climate Change May Benefit Some Salmon Populations. Concurrent with changing climate, some salmon populations and species have experienced unanticipated strong runs (e.g., Bristol Bay sockeye salmon and many pink salmon populations), but for others, survival at sea has been poor over large portions of the range (e.g., Chinook salmon: Kilduff et al. 2014, 2015). Determining the role of climate in survival is complicated by inter- and intra-specific competition among salmon at sea (e.g., Ruggerone et al. 2005, 2023), their diverse diets (Beamish 2018, Quinn 2018), changes in abundance of potential prey (Thayer et al. 2014), and sudden increases in such organisms as pyrosomes (Schram et al. 2020) that seem inedible for salmonids but may serve as nutritional sinks (O'Loughlin et al. 2020). Crozier et al.'s (2021) life cycle model, applied to eight Snake River Chinook populations predicted drastic declines in response to the anticipated warming climate, chiefly due to impacts in the marine life stage where survival was reduced by 83-90%. However, considerable caution should be taken when applying these model results to other species and runs.

Temporal Patterns of Survival and Exploitation: For many decades it has been widely understood that the vast majority of smolts entering the ocean do not survive to recruit to fisheries or return to spawn, that much mortality occurs soon after ocean entry and before they recruit to fisheries, and that this mortality varies greatly from year-to-year (e.g., Parker 1962; Ricker 1964, 1976). Ten-fold variation in survival of salmon at sea among years is routinely observed in long-term datasets (Quinn 2018). Disentangling mortality that may be climate-related from direct causes of natural and fishing mortality is difficult. The development and wide use of the coded-wire tag (CWT: Johnson 1990) program increased understanding of the magnitude of both fishing and natural mortality, as well as the processes correlated with the latter. The ISAB's recent report on smolt-to-adult return (SAR) and survival (SAS) metrics (ISAB 2025-1) emphasizes that survival at sea, including density effects, fisheries, predation, is complicated and that climate plays a major role.

The Pacific Salmon Commission's Chinook Technical Committee (2025) provides a recent summary of smolt survival and fishery exploitation information for Columbia River Chinook (and other populations) based on the analyses of CWT data; ISAB 2025-1 reports on findings specifically from the Columbia River Basin. Smolt-to-adult survival (SAS) and return (SAR) are important metrics used to monitor the status and trends of Columbia River salmon (ISAB 2025-1). CWT indicator stocks include an aggregation from the lower and upper Columbia that are assumed to represent other stocks with similar biology and location of origin. It is important to understand the role of fisheries in determining abundance patterns, and although survival patterns are not entirely controlled by climate, they reflect in part the changing climate's role.

Fishery exploitation rates and survivals vary among Columbia River stocks and years (ISAB 2025-1), and many CWT indicator stocks experienced substantial survival declines in recent years (CTC 2025). For the most recent brood year (2024), most Columbia River stocks were exploited at about 35-50% with some as high as 75% (CTC 2025: Table 3.5). Ongoing monitoring of fishery exploitation rates is important, and adjustments to fisheries are potentially an important mitigation strategy for stocks particularly vulnerable to climate change and at-risk of extirpation.

Marine Mitigation Strategies: Many are surprised to learn that total numbers of salmonids in the Pacific Ocean are higher now than at any time in the previous century, in large part due to ocean warming that has primarily benefited pink salmon, combined with large releases of hatchery salmon (Connors et al. 2025). Between 25 and 40% of total salmon biomass (depending on what life stages are included in the estimates) is made up of hatchery fish (Ruggerone and Irvine 2018, estimates updated by Connors et al. 2025). Pink and chum salmon dominate, many of which are produced in hatcheries in Alaska and Japan, and there is evidence that pink salmon abundance affects the growth and survival of other salmon species (Ruggerone et al. 2005, Ruggerone and Connors 2015, Ruggerone et al. 2023). Most of the studies have considered effects on more northerly (e.g., Bristol Bay) salmon populations, but density dependent effects on growth and survival in the ocean have been examined recently for Snake River steelhead. These fish spend much of their marine lives in the Gulf of Alaska, where they overlap with much more abundant pink salmon. The steelhead populations studied were smaller in odd-numbered return years, when pink salmon runs are strongest (Vosbigian et al. 2024). Evaluation of growth and survival differences between even and odd years for other salmonid species and populations within the Columbia Basin salmonids is warranted. If competition at sea with abundant hatchery salmon limits the production of Columbia River salmonids, Columbia Basin managers should consider seeking coastwide reductions in hatchery salmon releases (Connors et al. 2025, Holt et al. 2008, Irvine 2025).

In addition to informed management of upstream flow patterns to minimize fish habitat disruptions in the Columbia River estuary, potential marine mitigation approaches include adjustments to fisheries for stocks particularly vulnerable to climate change and at risk of extirpation, as well as reductions in releases of hatchery salmon that compete with and negatively impact Columbia River salmon.

3. Lessons Learned for planning efforts, actions, and tools used in the Columbia River Basin

3.1. Introduction

This section reviews the lessons learned from initial efforts to address climate change within planning for fish, wildlife, and ecosystem management. Such lessons came from examples of successful design and implementation, from failures due to incomplete understanding of the climate impacts or the system's response to the planned actions, and from limitations imposed by standards of practice, societal values, and regulations.

3.2. General Findings and case study examples

3.2.1. Planning and prioritization strategies

Managers often must triage their limited budgets to protect priority populations, and careful analysis is needed to allocate resources and support decisions. Because managers cannot address every priority at once, much less accomplish all tasks, information supporting the decisions must be rigorously obtained, strategically prioritized, and transparently processed, while considering the diverse stakeholder perspectives.

Principles and frameworks for prioritizing restoration and mitigation actions range from simple to comprehensive. A simple strategy would be to forego habitat restoration in places that will be dewatered or too warm for salmonids in the future, or to prioritize survival of a population during extreme heat or water years (Crozier 2024). Comprehensive strategies prioritize among many potentially suitable locations, as well as consider social, cultural, and economic data, traditional knowledge, and societal values and priorities. A key consideration is that planning for climate resilience should involve considering the needs and desires of Tribal governments and Indigenous communities, as well as other marginalized groups that exist on the frontline of climate impacts. The inclusion of social, cultural, and economic data where available is possible and should be encouraged. Scenario planning, which is a somewhat emerging practice and requires skilled facilitators to be effective, can help make social priorities more visible and amenable to ranking (NPS 2025a, 2025b; USGS 2023; Tribal Climate Adaptation Guidebook 2022; USGCRP 2023). Finally, we acknowledge that federal law may mandate actions to maintain populations regardless of their future viability in the face of climate change (e.g., long-term captive propagation and population supplementation of federally listed Rio Grande silvery minnow, Archdeacon et al. 2023). With these considerations in mind, we provide some examples of prioritization and planning frameworks in the Columbia River Basin.

Tribal leadership in climate resilience assessment and planning: The Tribes of the Columbia River Basin have taken an important leadership role in developing, documenting, and implementing climate resilience actions, including inter-tribal collaboration. For example, a core team of Upper Snake River Tribes (USRT), Upper Columbia United Tribes (UCUT), and Columbia River Inter-Tribal Fish Commission (CRITFC) are maintaining a searchable database for its ongoing actions (Tribal Climate Resilience Action Database). Other examples are occurring within individual tribes, as described below.

USRT tribes have focused on climate change as a key challenge to the management of tributaries of the upper Snake River (Hauser 2025 presentation). USRT has long recognized the threat from changing climate on their restoration efforts. Beginning in 2016, USRT completed a Climate Change Vulnerability Assessment (all documents referenced in this section may be viewed at www.usrtf.org) to assess the risks posed by changing climate. This vulnerability assessment was followed by an overarching planning document, Climate Adaptation Planning: Strategy Workbook, Pilot Projects, and Videos in 2019 to guide and promote their initial activities, Tribal Climate Hazard Mitigation Planning document, and an online database that tracks resilience actions. Together these documents, videos, and databases serve as USRT's climate change framework (see also native-climate.com/projections for temperature and precipitation forecasts).

In a related and complementary set of activities in the Snake River Basin, the Nez Perce Tribe (NPT) is focusing on an action plan and framework for addressing climate change (see briefing to the ISAB provided by Krantz 2025). Because of historical activities across the area, there are many degraded conditions and threats to anadromous and resident fishes and wildlife. The NPT judges that climate change compounds these historical threats and risks and adds novel challenges to managing biota in the area. In response, the NPT has conducted a vulnerability assessment and compiled a Nez Perce Tribe Priority Climate Action Plan. Viewed as a preliminary set of actions with others to be identified soon, these actions address eight priority measures for reducing carbon emissions and other forms of pollution. The NPT views the climate crisis as one that can be confronted and even reversed. Moreover, addressing the climate crisis is embedded in the Tribe's close ecological relationships and with its sovereignty. As such, they are guided by ranked solutions outlined at Project Drawdown and Regeneration.org. From these ranked solutions, one of the highlighted actions viewed as cost-effective was through afforestation as a carbon sequestration action.

Prioritizing youth: The USRT has undertaken some unique activities to engage their community, especially youth. First, a program entitled Climate-Based Community Outreach and Education is a general public program to demonstrate the need and potential awareness of climate issues. Second, the Tribes are creating a program entitled "Environmental Justice Collaborative Problem-Solving" aimed at youth to connect the issues of and solutions to climate change as social and environmental justice concerns. The program also aims to recruit young future leaders and provide the tools and skill sets necessary for addressing climate change.

Resist, Accept, Direct (RAD): The RAD framework (Williams 2022) acknowledges that some of the changes facing ecosystems are increasingly difficult and expensive to address, particularly as climate change intersects with other stressors such as invasive species, land use changes, and pollutants in the air and water. The framework aims to "help decision makers make informed, purposeful, and strategic choices" (NPS 2025b) about how to invest resources in ecosystems undergoing change. Conceptually, ***Resist*** involves working to maintain or restore ecosystem features and functions, and it can include things like building new habitats or removing invasive species. ***Accept*** refers to a choice to let the ecosystem evolve without intervention, even if it means populations are replaced or extirpated. This can occur where it is too expensive to remove an invasive species, the invader provides some functions, or environmental conditions can no longer sustain a population. ***Direct*** involves activities that steer an ecosystem towards a specific outcome or desired state. Examples include purchasing conservation easements northward of historical habitats or transferring taxa outside their historical range. A key feature of the RAD framework is transparency and collaboration in choosing which battles to fight and how to fight them. The Accept approach is the space in which lowest priority species or groups receive little effort, but this is done with transparency, deliberation, and consistency with legal requirements in a collaborative approach with all partners at the table rather than through a lack of action.

Habitat Assessment and Restoration Planning (HARP): HARP (Beechie et al. 2023a) is a life-cycle-based framework that was developed to support prioritization of salmon habitat restoration for salmon recovery and resilience. It can represent landscape-scale changes and scenarios (e.g., climate change, land use change, habitat restoration) through the modification of parameters that define habitat conditions and life stage vital rates. Model results allow across-scenario comparisons of population abundance and productivity and have been applied in multiple river basins in Washington. Social values are not explicitly or implicitly represented within this framework.

Atlas Restoration Prioritization Framework (ATLAS) and the Grande Ronde Model Watershed (GRMW): The GRMW conducted a coordinated and comprehensive adaptive management program for the Grande Ronde and Imnaha watersheds. Activities in the watershed historically were guided and prioritized from ATLAS (BPA 2017). ATLAS is a stepwise framework to identify the reaches at greatest risk and needed restoration or mitigation actions. Importantly, a recent addition to the ATLAS framework is the climate change attributes following Beechie et al. (2023a, b). Scoring includes climate-related attributes such as flow and thermal limitations, forecasted (future) impairments, land use and development, and use by anadromous fish at critical life-history stages. As a specific example of how data have been used to prioritize restorative and protective actions within the GRMW framework, Justice et al. (2017) used

NorWeST stream temperature models to identify headwater reaches for fish use (e.g., relative to Chinook spawning grounds), opportunity to restore (e.g., current v. potential shade), and predicted benefits (e.g., models showed that restoring vegetation and stream width characteristics should significantly reduce water temperatures). Here, elevated water temperatures in the headwaters and downstream migration corridors were considered a primary limiting factor, especially under future conditions. ATLAS is also used to prioritize actions on the landscape. For example, it has been used to identify reaches with "stepping stones" of thermal and hydrological refuges. The strategy is not specific to addressing impacts from changing climate, yet it is a critical element to consider for migrating fish through the system. Conversely, in the upper reaches of the watershed, actions to provide climate resilience are prioritized, including riparian shading and cold water retention through installation of beaver-dam analogs and other actions that benefit the headwaters and downstream reaches. The GRMW partnership conducts a wide range of RM&E on physical habitat and fish response evaluations as part of their adaptive management framework. Important elements of this adaptive management framework are the annual State of the Science meetings and reporting and periodic reviews to assess program progress, identify new tools or analytical assessment approaches, or modify strategies.

Climate resilience assessment: The Climate Resilience Index (Adams and Zimmerman 2024), developed for the Washington coast, translates science into a tool for scoring projects and prioritizing efforts to improve climate resilience for salmon. The online tool reflects results of projecting future conditions and estimating impacts on salmon species and life stages through an index. The index combines existing and remotely sensed data to develop metrics on climate exposure, ecological sensitivity, and social adaptability, reflecting local values and institutions such as regulatory effectiveness and voluntary receptiveness, documented through participatory working groups. The online tool and report cards help funding agencies and managers understand the metrics and site characteristics underlying the resilience index. The process is locally oriented, so the metrics and weighting schemes will change when the tool is applied in other settings.

Linking thermal refuge habitats to high priority climate risks: While temperature is a key climate-related risk, aquatic organisms require other resources, many of which are threatened by climate change (e.g., food, adequate water quantity and quality, spawning substrate, low disease risk, and shelter from predators). A climate-resilient strategy can help identify and map refuges and strongholds for climate-related risks (Figure 7), and help prioritize actions to promote refuge duration, connectivity, and effectiveness (Ebersole et al. 2020).

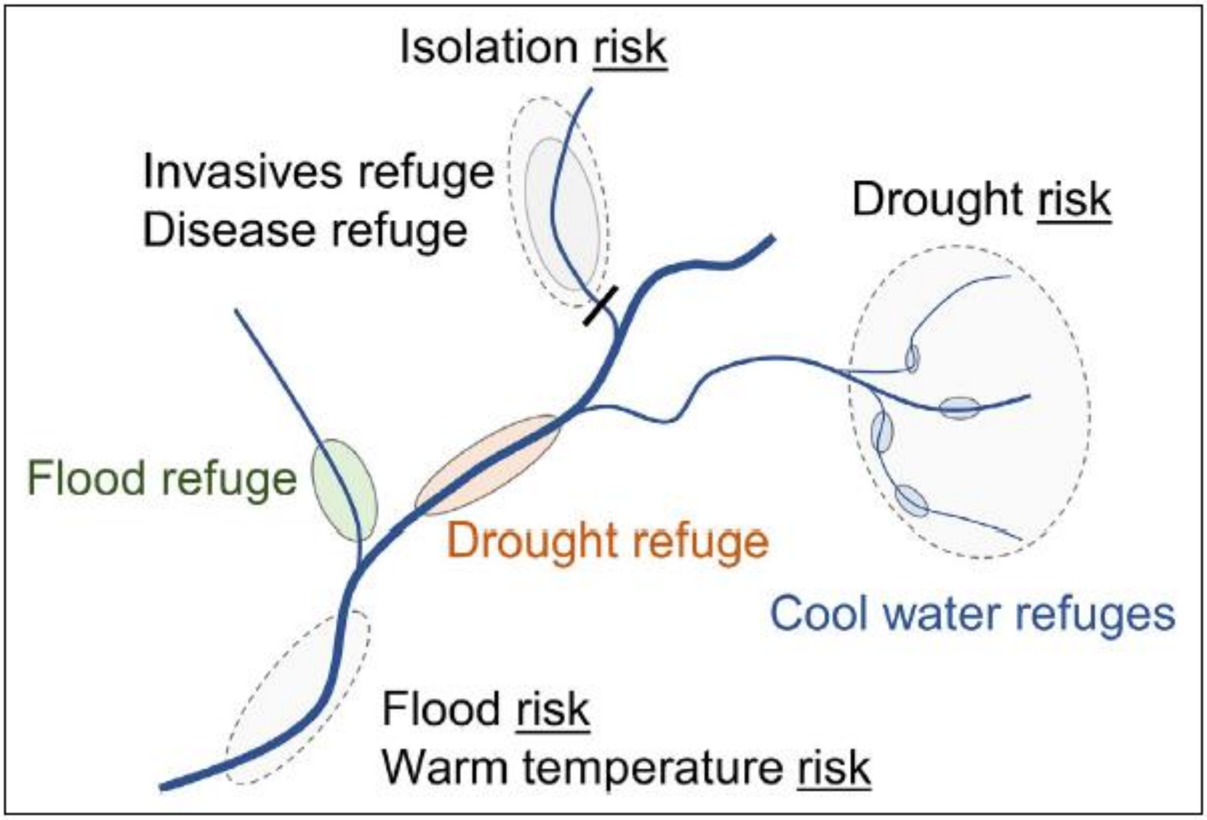

Figure 7. Thermal (or, cool/cold water) refuge habitats protect against climate-related risks. "Refuge habitats (solid ellipses) for coldwater fishes provide short-term shelter from risks (dashed ellipses) but are also critical for long- term species persistence within the stream network that, as a whole, constitutes a climate refugium." (Source: Ebersole et al. 2020)

Climate-inclusive conservation in the Lower Columbia River: Since 2007, climate-focused efforts in the Columbia River estuary have been undertaken independently and collaboratively among state and federal agencies, tribal authorities, local governments, and formal partnerships (e.g., the Lower Columbia Estuary Partnership). Collaborative actions have been guided by two conceptual frameworks. First is the application of "Climate-Smart Conservation" practices: actions that can withstand and mitigate climate impacts. Conceptually, Climate-Smart Conservation accepts that changes will occur and need to be accommodated. Goals are forward-thinking and recognize the new dynamic processes rather than a static, historical set of conditions (Stein et al. 2014). Second is the "Climate Adaptation Framework" that describes multiple spatially explicit adaptation approaches to conserve biodiversity (Schmitz et al. 2015), such as protecting large intact natural landscapes, ecological processes, and geophysical settings; maintaining or reestablishing connectivity to permit movement and access to habitats critical to sensitive life-history stages; and protecting or re-establishing climate refuges (Schmitz et al. 2015).

Strategic prioritization of conservation in the estuary: The Expert Regional Technical Group (ERTG 2024) is a program structured around habitat project evaluation criteria that include scoring screens or filters that are mindful of changing climatic conditions with an aim toward improving resilient outcomes for the Columbia River estuary. ERTG (2024) recommends optimizing project locations, designing self-maintaining projects, reducing uncertainties in project outcomes, and undertaking well-monitored pilot projects to demonstrate proof of concepts. Included in the 2024 ERTG report are the identification of high-priority locations, design specifications, monitoring (RM&E) for effectiveness, and progress at improving resilience to shifting conditions associated with forecasted climate change (ERTG 2024). The framework also provides guidance on specific factors that enhance climate resilience (Pelletier et al. 2020), including connectivity and heterogeneity of functional habitats, life history diversity and redundancy, and links among ecological and social (human) systems.

Value from framing analytical approaches based on key questions. For the Columbia River Basin, data analyses and modeling can address important questions such as: Where do strongholds exist, and where will organisms be most able to thrive in the future based on environmental gradients? Are there alternate locations for critical habitats (e.g., spawning habitat downstream of dams) and what is the cost and sustainability of establishing those habitats? Where might aggressive management of predators and invasive species be effective? Where are temperature refuges or hydrological mitigations to buffer climate effects likely to provide population-level improvements? In short, data analyses need to address critical questions relevant to target species at spatial scales and identify stressors contributing to species' declines or hindering ecosystem function.

3.2.2. Analysis and modeling tools

Planning for climate-resilient habitat restoration involves the integration of past best practices, expert opinion, environmental and biological data, and models that estimate habitat and/or fish responses to future habitat or climate change scenarios. Many of these data sets, modeling tools, and information repositories are accessible from websites (Table A1, see Appendix). The types of models that are used, often in combination, predict or simulate (1) temperature and flow in rivers and the estuary, (2) habitat suitability, (3) fish bioenergetics, vital rates, and life-cycle population dynamics, and (4) movement or particle-tracking for connectivity.

Habitat suitability and life cycle modeling are closely aligned with the population-level scales of response that are typically of primary interest to project partners and the goals of restoration (enhancing fish populations; ISAB 2025-1). Habitat suitability models (HSMs) link environmental covariates to indices of a habitat's suitability for supporting fish use. Ecosystem Diagnosis and Treatment (EDT) modeling takes HSMs a step further by integrating a model of habitat suitability with life history simulations to predict several metrics of population performance. Life cycle models (LCMs) explicitly represent the processes that determine vital rates, so they can be combined across space and life stages in a simulation to predict population abundances and dynamics. In theory, the inclusion of ecological mechanisms in LCMs should enable better extrapolation to novel conditions (expected under restoration and climate change) and easier identification of cause and effect (see Sugihara et al. 2012). With LCMs, climate change effects and habitat actions are incorporated by explicitly including their effects on growth, mortality, reproduction, and/or movement. Figure 8 shows the relationship between HSMs, LCMs, and EDT.

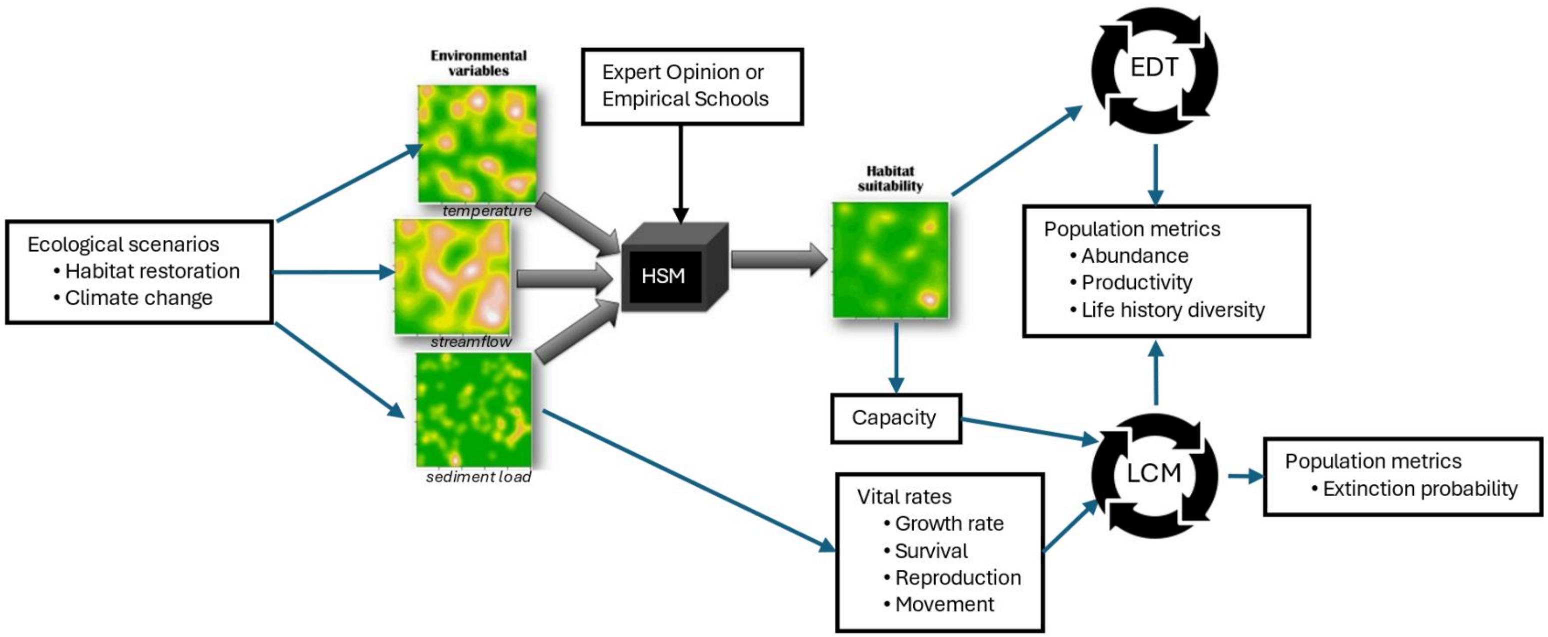

Figure 8. A schematic showing the basic relationship between HSMs, LCMs, and EDT. HSMs translate environmental variables and information on fish to create a habitat suitability surface of species occupancy or density. HSMs can vary in their use of empirical data and expert opinion, and in their structure, complexity, and outputs. Habitat suitability at a site level then translates to habitat capacity for a particular life stage. Environmental variables also can affect vital rates such as survival. Site- and stage-specific capacity and survival are used in the stock-recruitment relationships that are components of LCMs. Adjustments to environmental variables via habitat restoration and climate change or their downstream outputs (habitat suitability, capacity, survival) allows modelers to explore how climate change and habitat restoration scenarios affect LCM outputs (abundance, quasi-extinction probability). EDT modeling combines habitat suitability modeling and life history simulations to predict population abundance, productivity, and life history diversity. The habitat suitability graphic is modified from Figure 2.1 in Matthiopoulos et al. 2023.

A suite of physical and ecological models is available and used in the Columbia Basin for informing design, prioritization, and scoring of proposed projects (ERTG 2022). Several of these models, and other analytical frameworks, include habitat suitability as part of their calculations.

These analytical frameworks include:

- Expert Opinion School-based analyses (e.g., Judd et al. 2013, White et al. 2022)
- Habitat Intrinsic Potential Analysis (Cooney and Holzer 2006, Shallin Busch et al. 2013)
- Ecosystems Function Model (Hickey et al. 2015, 2025)
- Habitat Restoration Planning (HARP) model (Jorgensen et al. 2021, Beechie et al. 2021, 2023a), and
- Ecosystem Diagnosis Treatment (EDT; Blair et al. 2009).

In some applications, multiple modeling approaches that include habitat suitability are used (e.g., Roni et al. 2023, UCUT 2019). To illustrate how habitat suitability can be embedded in these models, we provide more details for EDT in Box 3.1. Other models use a similar approach of relating explanatory variables to scored suitability classification.

Box 3.1: Explanation of how habitat suitability is incorporated in the EDT model.

EDT is a habitat-based model that is commonly used in the Columbia Basin (Lestelle et al. 2004, Lestelle 2005, Blair et al. 2009, Lestelle and Morishima 2020, Doyle et al. 2022). EDT goes beyond habitat suitability models by incorporating aspects of life cycle modeling but is not a full life cycle model. Predictions are expressed as life-stage specific abundances. EDT characterizes environmental variables (termed Level 2 variables) relevant to salmonids (e.g., physical habitat, water quality, competitors, predators, pathogens, macroinvertebrate food availability) on a reach scale at monthly intervals. **Essentially, the assignment of sensitivity values (scaled zero to one) to categories of each Level 2 environmental variable** (e.g., Doyle and Lestelle 2021, Lestelle and Doyle 2021) **are analogous to the univariate suitability functions used in habitat suitability modeling**. Expert opinion and various data sources are used to estimate the sensitivities in EDT. These are then combined (termed Level 3 variables) to affect life-stage specific survival and capacity in Beverton-Holt functions for each reach and stage. EDT then uses a random sampling approach to ensure coverage of the many possible pathways individuals can take (trajectories) through the life history space and the connected habitats. Accumulating the survival of these trajectories results in prediction of life stage abundances and reach capacities. Similar cautions about how to appropriately interpret classical habitat suitability also apply to EDT predictions.

EDT modeling is commonly used in the Columbia River Basin for habitat restoration planning (review: ISAB 2025-1) but it rarely incorporates local climate change scenarios. For example, for Umatilla Subbasin summer steelhead (Wooster et al. 2019), climate scenarios were based on output from global climate models (GCMs), assumed to affect survival via changes to water flow and temperature. Habitat scenarios were based on levels of agricultural intensification and corresponding loss of riparian vegetation, which were assumed to affect survival via changes to oxygen, sediment load, toxins, habitat diversity, channel stability, and temperature. Because climate and habitat stressors varied in their magnitude and influence across the basin, impacts also varied among life stages.

Because modeling changes in habitat is fundamental to representing climate change impacts on management and restoration, we discuss aspects of best practices related to habitat suitability modeling in the report's Appendix. Methods for temperature and flow modeling are relatively well-established, and models are generally known and useable. Life cycle modeling can be complex and is usually conducted by specialists who know and follow best practices guidelines. Movement modeling to assess connectivity is not commonly conducted as a standalone analysis in the Columbia Basin, but movement sub-models are often part of spatially resolved life cycle models. Some of the practices in the Appendix also apply to temperature/flow, life cycle, and movement modeling.

Several LCMs have been developed and used in the Columbia River Basin to project the population-level responses of anadromous salmon to alternative ecological or management scenarios involving aspects of habitat restoration (Pess and Jordan 2019), future climate conditions (Zabel et al. 2006, Crozier et al. 2008b, 2021), or a combination of alternative climate and habitat conditions (Honea et al. 2017, Beebe et al. 2021, Zabel and Jordan 2020 and chapters therein). Table 1 describes some key features of LCMs that address alternative climate scenarios in combination with habitat restoration actions. LCMs have also been used in nearby watersheds outside of the Columbia River Basin to evaluate scenarios that involve future climate and/or habitat conditions (Battin et al. 2007, Beechie et al. 2021, 2023, Fogel et al. 2022, Jorgensen et al. 2021, Nicol et al. 2022). Efforts to develop LCMs to inform management in the Columbia River Basin have focused on anadromous salmon, but there is a recent exception for Pacific lamprey (Gomes et al. 2025). LCMs are useful but not static and need updated inputs, structural refinements, analyses of sources of variation, key uncertainties, and assumptions, and strategies for communicating results if they are to remain effective over time (ISAB 2017-1).

Table 1. Applications of LCMs in the Columbia River Basin that evaluate alternative climate with or without habitat scenarios involving restoration, organized by species and subbasin. The specified climate and habitat drivers relate to the alternatives under consideration, and other climate or habitat effects may be present in the model.

Reference	**Subbasin or population**	**Climate driver**	**Climate alternatives**	**Habitat driver**	**Habitat alternatives**	**Output**
Zabel et al. 2006	Snake River spring/summer Chinook (aggregate)	PDO affects estuary and early ocean survival	Subsets of historical data	Density dependent FW life stage transitions	Not considered	Spawner abundance, quasi-extinction
Crozier et al. 2008b	Snake River spring/summer Chinook (4 populations)	Stream flow or temperature affects juvenile survival	Outputs from GCMs	Density dependent FW life stage transitions	Not considered	Spawner abundance, quasi-extinction
Crozier et al. 2021	Snake River spring/summer Chinook (8 populations)	FW and marine environmental covariates affect survival and migration timing	Outputs from GCMs	Density dependent FW life stage transitions	Not considered	Spawner abundance, quasi-extinction
Cooney et al. 2020	Snake River spring Chinook (Grande Ronde River)	FW and marine environmental covariates affect survival and migration timing	Outputs from GCMs	FW habitat affects FW survival and rearing capacity	Proposed restoration of FW and riparian habitat	Spawner abundance, quasi-extinction
Jordan et al. 2020	Snake River spring/summer Chinook (Upper Salmon River)	FW and marine environmental covariates affect survival and migration timing	Outputs from GCMs	FW habitat affects FW survival and rearing capacity	Proposed restoration of habitat quality and quantity	Spawner abundance, quasi-extinction

Reference	Subbasin or population	Climate driver	Climate alternatives	Habitat driver	Habitat alternatives	Output
Honea et al. 2017	Wenatchee River spring Chinook	Stream temperature affects FW survival and movement	Outputs from GCMs; higher scour	Terrestrial habitat affects FW survival	Landscape attributes	Abundance
Jorgensen and Bond 2020	Wenatchee River spring Chinook	FW and marine environmental covariates affect survival and migration timing	Outputs from GCMs	FW habitat affects FW survival and rearing capacity	Proposed restoration of habitat quality and quantity	Spawner abundance, quasi-extinction
Beebe et al. 2021	Lower Columbia coho (1 population)	Assume drought reduces rearing capacity	Indirect via habitat	Density dependent FW life stage transitions	Rearing capacity	Spawner abundance, quasi-extinction

FW = freshwater, GCM = global climate model, PDO = Pacific Decadal Oscillation, MPG = major population group, RCP = representation concentration pathway, SST = sea surface temperature.

Analytical and data improvements: Advances in statistical modeling and the development of large-scale stream network datasets and their hydrological characteristics (e.g., NHD-Plus, Moore and Dewald 2016), particularly stream temperature (e.g., NorWeST, Isaak et al. 2017), made it possible to better predict changes in habitat occupancy in light of climate change for salmonids (Wenger et al. 2011, Heinle et al. 2021). The increasing sophistication of these models (e.g., SSN models, Ver Hoef et al. 2014), coupled with improved field sampling of cold-water streams (e.g., environmental DNA sampling and analysis: Carim et al. 2016; databases: Young et al. 2018), have resulted in new tools for advancing climate resilience. These tools include whole-basin assessments of salmonid or Pacific lamprey recolonization or presence (Duda et al. 2021, Young et al. 2022a, Elmore et al. 2025), demonstrating the importance of connectivity or habitat size to population persistence (Isaak et al. 2022), and documenting the influence and distribution of non-native species (Wilcox et al. 2018, Winkowski et al. 2024).

3.3. On-the-ground approaches to climate resilience in the Columbia River Basin

While many river restoration practices are implemented within and outside river channels, the briefings and literature suggest that a few actions are likely to be most effective at mitigating the effects of, or increasing resilience to, climate change's most likely impacts. This summary emphasizes actions that can be taken in freshwater environments where program managers and practitioners have some control. Other management actions may also contribute to ecosystem resilience to climate change, including non-native and invasive species control, evolving wildfire management, reduced harvest of overexploited populations, reduced hatchery releases for overcrowded populations, and carbon accounting in restoration planning (Corbett 2024 presentation).

Approach 1. Increase lateral and longitudinal connectivity.

Connectivity is essential to sustaining life in changing rivers (Thoms 2003, Hohensinner et al. 2004, Rudnick et al. 2012). Reconnecting a river longitudinally and laterally with its floodplain increases resilience to climate change by expanding access to and movement across environmental gradients, including access to refuges during extreme events. Floodplain protection and reconnection provide excellent opportunities to counteract the impacts of climate change (Gary James/CTUIR, 2022, Slide 17), and the literature is rich with examples of the benefits of restoring longitudinal and lateral connectivity of rivers. For example, increasing lateral connectivity, through floodplain and off-channel reconnections and levee setbacks, can provide critical off-channel habitats that are refuges during high flows and rearing areas for young fish (King et al. 2003, Rosenfeld et al. 2008, Kroboth et al. 2020). Additionally, increasing connectivity among fragmented habitats longitudinally, through dam removal and flow restoration, provides organisms access to a wider array of habitats when access to or quality of historical habitats is lost.

Connectivity can also directly mitigate some effects of climate change. For example, wet floodplains can reduce the spread and growth of fire footprint and intensity (Figure 9) and alter landscape-scale fire behavior by acting as fire breaks. Inundated landscapes can also increase water infiltration into the ground where it cools and is later delivered to streams.

Figure 9. Reconnected section of the Sycan River following the 2021 Bootleg fire (source: Sarah Koenigsberg). Reconnected floodplains and wet meadows can be refuges of unburned areas during a wildfire.

Approach 2. Identify, maintain, and enhance cold-water refuges and climate refuges.

Because salmonids are coldwater ectotherms, albeit with different thermal preferences (Isaak et al. 2017), the amount, distribution, and accessibility of cold water often dictates the extent and viability of their populations. The motivation for identifying areas of cold water is context-dependent. In larger rivers, cold-water refuges reflect localized areas of cold-water upwelling or lateral plumes often associated with tributary junctions (Ebersole et al. 2020, Sullivan et al. 2021). These refuges can be temporarily occupied by dozens to hundreds of individuals when nearby habitats become too warm and from which they depart when temperatures cool. Alternatively, climate refuges are thermally suitable habitats sufficiently large to sustain entire populations throughout all or part of their life history (Isaak and Young 2023). Recent technological developments have made it feasible to map the location of cold-water plumes in large rivers with exceptional precision (Handcock et al. 2012). Likewise, regional water temperature datasets (Isaak et al. 2017) have made it possible to identify cold tributary reaches likely to serve as natal habitats for cold water species, including those most likely to constitute a "climate shield" that will sustain populations throughout the 21^{st} century as conditions continue to warm (Isaak et al. 2015, 2022). Both efforts are enabling planners to focus efforts where restoration is most likely to be successful and recognize locations that may not remain habitable regardless of conservation efforts. Protecting and providing access to refuges in a warmer climate will need to include and go beyond current tools, including identifying cold water habitats and implementing threshold temperature standards (Mejia et al. 2023). Additional tools for increasing availability of cold-water refuges, or temporarily protecting the fish within them, may include conservation of groundwater recharge areas or restricting fishing during warm periods, as well as adopting temporary or long-term water management practices that increase hyporheic flow or cold water tributary discharge (Kurylyk et al. 2015), and expanding access to cold headwater reaches via barrier removal.

Approach 3. Address riparian shading and other thermal loads.

While pockets of cold water can provide refuge in a warm environment, larger-scale reduction of thermal loading is needed to restore water quality. Thermal loads to rivers originate from urban stormwater (Jones and Hunt 2010), municipal wastewater and other industrial effluents (Kinouchi et al. 2007), and from the removal of riparian vegetation that increases exposure of streams and rivers to solar radiation (Rutherford et al. 1997). Beyond the engineering and nature-based solutions needed to address urban and effluent loads, preserving and restoring riparian vegetation is an important climate adaptation and mitigation tool (e.g., Beechie et al. 2023b). Justice et al. (2017) demonstrated how large-scale restoration of riparian vegetation could offset the substantial expected increases in water temperatures (1.5 to 2.7^{o}C) and reduce effects of rising temperature on Chinook salmon parr in the upper Grande Ronde River Basin, though the effects of shading in mitigating water temperature can vary across hydrogeomorphic conditions (O'Briain et al. 2020, Johnson and Wilby 2015).

Approach 4. Actions that emphasize dynamism to support adaptation to changing conditions.

Design philosophies in river restoration are shifting from a historical prioritization of engineering resilience (sensu Holling 1996), which emphasized rivers that are stable and unchanging when faced with disturbances in, for example, flows and temperatures. Recognizing the need for systems to adapt as land use, water infrastructure, and climate change, design is moving towards a more ecological view of resilience, whereby systems can adapt and maintain their structure and function, even as aspects of the system change. In practice, this design approach involves creating more space and flow paths for the river and giving it the materials it needs to organize itself:

- Connecting multiple off-channel surfaces to store floods of different sizes as flood regimes change (Call et al. 2017).
- "Rewetting the sponge" to recharge declining groundwater, reduce concentrated forces from intensifying floods, improve water quality, and provide surfaces for plants to self-organize and grow.
- Creating physical structure that can sort sediments into diverse and dynamic bedforms that support diverse aquatic communities.
- Spreading out hydraulic forces rather than building structures to withstand them when future peak flows are uncertain.

This transition is based on the understanding that rivers can recover from disturbances best when given the space to flood, erode and deposit sediment, recruit trees, and form different channel configurations (Castro and Thorne 2019, Cluer and Thorne 2014, Kondolf et al. 2006, Piégay et al. 2005, Fuller et al. 2019, Raven et al. 2010).

Designing for dynamism can be in tension with classic views of engineering design that imply certainty that a system will function and look a particular way. This concept is embedded in federal regulations as part of a broader societal strategy on risk management. With the rising spread of uncertainties around all aspects of water and ecosystems, infrastructure designed based on a fixed expectation of the future is more likely to fail (Tullos et al. 2021). How risks are distributed will change from the condition that existed at the time habitat and mitigation projects are designed, and current design-life approaches rely on calculations made without knowing the future design parameters and when design conditions change substantially over a project's design life. Instead, climate-resilient projects approach restoration design as a starting point, removing constraints and barriers, and allowing rivers to evolve. Traditional engineering calculations are still a check but are not the basis of design. Re-naturalization practices (Figure 10), such as levee removal and setbacks, reintroduction of large wood to initiate lateral erosion, and dynamic, multichannel configurations, use space to promote dynamism over stabilization as a strategy for long-term resilience and risk reduction.

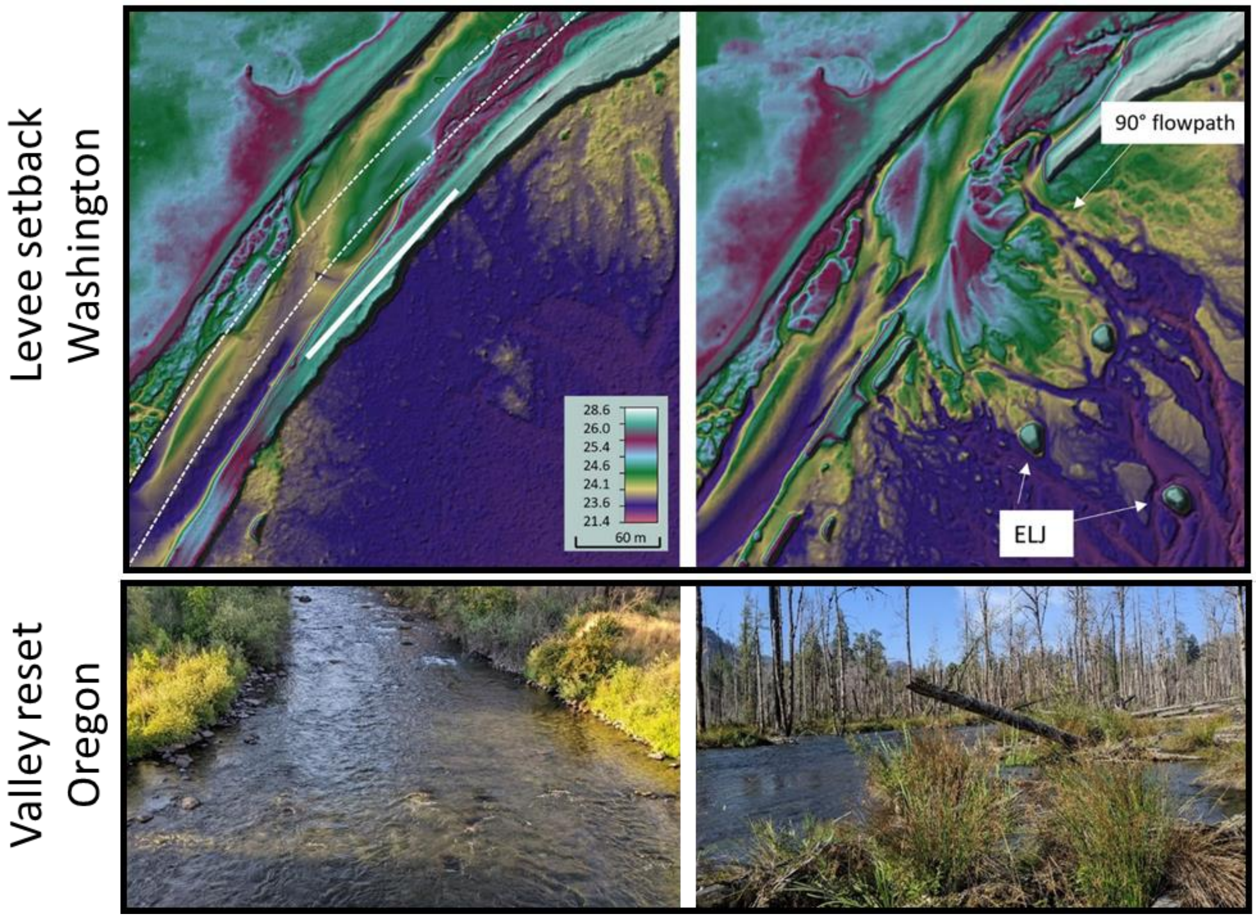

Figure 10. Treated and untreated conditions for a levee setback in Washington and a valley reset project in Oregon. Pre-project conditions are on the left. Post-project conditions are on the right. (Source: adapted from Curran et al. 2025 and Hahn et al. 2025).

Approach 5. Adjustments to dam operations.

Operations of water infrastructure can be modified to minimize their impact on the ecosystem and mitigate the temperature and flow effects of climate change. Increasing operational flexibility of infrastructure can be effective at responding to short-term variations in stream flows, temperatures, and fish populations. Operational decisions about whether to store or release water, and from which dam and which outlet, have documented benefits in supporting ecological resilience through a) operation of outlets to manage downstream temperatures using the cold water pool at the bottom of reservoirs, b) releases to accelerate water and fish transport time through hydrosystems (Cada et al. 1997), and c) adjustments of flow variability at a range of time scales to support a range of seasonal use patterns (Poff et al. 1997), among others. For example, beginning in 1992, flow releases from Dworshak Dam on the Clearwater River have been scheduled to reduce summer water temperature in the Snake River and tailrace of Lower Granite Dam to improve conditions for migrating smolts and adults and rearing juveniles (NMFS 2020a). While the benefits of more real-time, coordinated adaptive management have strong potential to support climate resilience, this shift relies on quality, timely data and engaged individuals across institutions to make informed decisions and communicate with the public. Resources need to be available to enable participants to stay engaged, and monitoring programs need to remain fully funded.

Approach 6. Population rescue and captive rearing.

Under extreme circumstances, it may be necessary to rescue populations of high-priority species that are under immediate threat of extirpation. A common example is rescue of salmonid populations in basins where debris torrents were expected following stand-replacing fires (Propst et al. 1992). In another instance, two Chinook salmon populations in the Sacramento River basin with an unusual migratory life history (Cordoleani et al. 2021) had declined to quasi-extinction levels (< 50 adults), and wild fish from these populations were brought into a conservation hatchery. In the Pacific Northwest, a program captures juvenile salmon likely to be trapped in intermittent streams and holds them until favorable conditions resume or they are released as smolts. Beebe et al. (2021) concluded that the demographic consequences of this program for populations of coho salmon could range from negligible to beneficial depending on the tactics adopted. As the effects of climate change become more pronounced and widespread, candidate populations for rescue may become more numerous and demographically synchronized (Copeland and Meyer 2011), with large numbers of populations at risk in some years. Therefore, assessing benefit – risk tradeoffs associated with rescue and captive rearing for conservation merits examination before these strategies are widely employed. The costs, infrastructure, and technical expertise required to implement broadly are unlikely to be trivial, therefore, prioritization schemes will need consideration upfront.

4. Guidance for climate resilient fish, wildlife, and river restoration

4.1. Recommended Principles

Recommendation 1: Strategic and transparent prioritization of actions that includes consideration of intersecting stressors is important at the outset of project planning.

In making decisions about on-the-ground activities to mitigate climate change effects (Section 3 above), project managers and decision-makers must consider how to allocate efforts and resources to maximize benefits. Science and Indigenous knowledge can inform decisions, such as identifying when a species is unlikely to persist without extreme intervention, the likelihood of success of a specific action, expected benefits from a specific action for a population, and which habitats are likely to be uninhabitable in the future. However, society and managers, not scientists, ultimately decide how to invest restoration and mitigation resources based on several priorities.

Resource decisions should be made transparently, through public engagement, and be based on information in hand. For example, the scientific community may identify locations that likely will be too warm in 30 years, and managers may choose to minimize investments in those locations. However, decisions should not be based on biophysical model projections alone. Planning and prioritization strategies need to include socio-cultural context and values, reflecting a need for greater collaboration between river restoration managers and socio-cultural scientists. Some existing frameworks exist (e.g., RAD, HARP) for making these decisions transparently (see Section 4.3.2 of this report).

Prioritizations and strategies need to consider other factors that interact with climate change besides habitat suitability. For example, harmful cyanobacteria blooms are increasing with water temperatures and other factors (Paerl and Huisman 2008, Dai et al. 2023, O'Neil et al. 2012, Ho and Michalak 2019; but see Hallegraeff et al. 2021). They can alter dissolved oxygen and pH, leading to damaged gills and livers, and decreased feeding of wild salmon (Esenkulova et al. 2022). Further, climate change is occurring within the footprint of changing and aging infrastructure. The increasing pressure from extreme floods and droughts can contribute to dam and gate failure and an inability of dams to store water for minimum flows and regulated temperatures downstream. Additionally, density dependent effects and changes to food webs and fish assemblages can result from factors beyond climate change. Propagation can be a critical transitional option while longer-term restoration of wild populations is underway, but hatcheries can bring a host of challenges and unintended consequences (Naish et al. 2007, Brannon et al. 2004b) that managers will also have to consider. Tradeoffs can also exist with managing native (e.g., northern pikeminnow) and non-native predators (e.g., smallmouth bass and walleye) and competitors (e.g., shad, brook trout). Strategies that do not consider these and other intersecting factors may not produce the intended benefits over the long term. Finally, being strategic about restoration requires data-informed analyses and collaboration and coordination among scientists, managers, and the public, reflecting a need to also prioritize resources for data collection, synthesis, and engagement.

Recommendation 2: Maintaining and enhancing physical habitat and species' life history diversity are priorities for increasing climate resilience.

Diversity tends to increase ecosystem resilience (Elmqvist et al. 2003 and many papers since) and flood infrastructure (DiFrancesco and Tullos 2014), hence restoration programs are increasingly prioritizing the preservation and restoration of life history diversity (Ruckelshaus et al. 2002) through actions that strengthen a salmon population's resilience to environmental variability. Similarly, the variability in the timing, age, and size of juvenile salmon when they leave their natal streams heightens their resilience (Beechie et al. 2006, Lindley et al. 2009, Miller et al. 2010, Satterthwaite et al. 2014, Sturrock et al. 2015). As Beechie (2024) noted (see also Crozier and Siegel 2025), vulnerability of salmonids to climate change includes adaptive capacity along with exposure and sensitivity to the changes. A central element of adaptive capacity centers on life history expression of genetic-level diversity both within and among populations (Allendorf et al. 2012, see especially page 288 for a description of the consequences of loss of evolutionary potential). This concept has also been incorporated into NOAA Fisheries approaches to Viable Salmon Population assessments (VSP, McElhany et al. 2000). Specifically, VSP is based on four considerations, two of which are spatial diversity and life history diversity of the population. Thus, as salmonids are exposed to changing climatic conditions and altered environments, a diverse set of life history and genetic traits are expected to present the greatest chances of adapting to these new conditions.

Restoration actions can support diverse life history patterns in a dynamic set of habitats over space and time (Ebersole et al. 1997), allowing species and populations to express their full suite of life history strategies (Herbold et al. 2018, Munsch et al. 2019). Similar to the portfolio effect (Schindler et al. 2010) from the financial sector, considering life history diversity as the portfolio, managers can spread risk across populations through variance buffering, achieved by connecting and restoring diverse habitats that populations can use as disruptions make some habitat inaccessible or unusable. However, infrastructure limitations, risk aversion, and traditional management and perspectives can limit the outcomes (Tullos et al. 2021). For example, reservoir spill operations drive population dynamics in the Columbia River Basin but do not benefit all life history patterns equally.

Climate refuges will be essential to providing resilience but will require designing habitat networks that support the expression of a full range of phenotypic and behavioral plasticity (Beever et al. 2017), connectivity among seasonal habitats (Fullerton et al. 2017), and routes for species to shift their ranges to newly suitable habitats (Rahel et al. 2008). If these efforts are not pursued or are ineffective and population loss appears imminent, assisted migration of priority populations (Dunham et al. 2011), even outside their ranges (Kissinger et al. 2024), may be necessary.

Recommendation 3. Climate-resilient habitats may require more lateral space, dynamism, and better monitoring.

Much of the work related to habitat restoration and mitigation is rooted in the practice of river engineering, which emphasized risk aversion and a perspective of resilience that involves resisting change (Holling 1996). This perspective, while warranted in some settings, is often poorly suited to the landscape-scale changes river ecosystems are undergoing including channel movement. When designs are based on flood and low flow frequencies derived from historical data, they are unlikely to provide their intended habitat and benefits in a future characterized by more extreme flows.

An alternate strategy requires releasing some physical and psychological control over the fate of rivers. Such a strategy would be guided by a different set of principles identified during the briefings to the ISAB and in the scientific literature. First, designs should remove constraints and barriers, to the degree compatible with existing infrastructure, consider design as a new starting point, and leave the outcome to the dynamism of natural processes. This approach acknowledges that we do not always know the future design parameters and provides physical space (lateral area and flood plain) and materials so the river channel can evolve laterally, and organisms can move as conditions change. Several recent habitat projects have adopted this approach, including levee setbacks, dam removal, Stage Zero/valley floor reset projects that aim to recreate high complexity and connectivity (Cluer and Thorne 2014), and a variety of floodplain and in-channel projects.

Second, projects are subject to regulatory constraints to protect life and property, but dynamism and risk management are compatible. Restoration practitioners and resource managers can still meet regulatory criteria and manage risk without sacrificing broader perspectives. For example, some log jams designed to engage a side channel are overengineered to not move at even the highest flows. This reduces benefits as flows change. Instead, large wood structures can be designed to adjust as flows change with adequate space (Curran et al. 2025). Designing with space for the river to adjust, rather than designing for a single dominant discharge, spreads hydraulic forces out across space, rather than building structures to withstand those forces. Under this approach, the traditional engineering calculations are still conducted as a check but are not the basis of design. Other elements of flexibility and dynamism may also be warranted for the design process, such as alternatives to “design-build” contracting and current regulatory permitting.

Third, while it is important to prepare the entire river ecosystem for evolution and adaptation in uncertainty, not just the in-channel habitat, emphasis on some processes and elements are likely to create greater wins for climate resilience. These priorities include increasing longitudinal connectivity (via barrier removals unless the barriers inhibit the range of invasive species; Fausch et al. 2009) and lateral connectivity (via floodplain reconnection), protecting and increasing access to cold water refuges, and structural elements that foster self-organization and complexity. Collectively, these elements may be summarized into a conceptual model of a river as a sponge, rather than a conveyance. Slow and messy conveyance of water, sediment, wood, nutrients, and other materials provides the resources for flexible, adaptable systems that can re-organize themselves as flows, fires, vegetation and temperatures change. This approach will create greater long-term resilience, so the system can adapt to changing conditions, rather than designing for a specific storm and hoping our models and climate policies accurately represent a very uncertain future.

Finally, as part of this transition in design philosophy, we need more creative monitoring. Current designs emphasize elements that are easy or required to measure, not necessarily what we should measure. Complex projects are harder to monitor, making success harder to demonstrate. Measuring success in these complex systems requires measuring different things that reflect the new approach. Fortunately, emerging technologies, particularly remotely sensed data, make it possible to better document project outcomes in a cost effective and feasibly scaled manner. For example, we can measure extent of canopy cover and how fast vegetation regenerates over time using data collected from drones. We can assess the full range of temperature variation, rather than average temperature, using Forward Looking Infrared (FLIR) instruments. We emphasize three key points regarding monitoring: 1) What we monitor matters; 2) We can measure design criteria for complex ecosystems; and 3) Our monitoring capabilities exceed our monitoring protocols, necessitating updated requirements and recommendations for monitoring.

Recommendation 4. Policy and regulations need to be adaptable and collaborative to integrate emerging science.

Science has made major advances in predicting the effects of climate change at a regional scale, which can inform climate-resilient policies. However, policy needs to be able to assimilate and use the new information as it becomes available.

In addition, during the briefings to the ISAB, a number of speakers raised concerns about barriers embedded within the current regulatory framework, which can lead to a system that functions and looks a certain way, similar to the design of a bridge, in that it is designed to remain unchanged. An important tension exists between regulatory guidance aimed at risk aversion and the need for flexibility to do innovative things. As part of a transition to restoration that prioritizes more dynamic areas with more accommodation space, projects will need to be faster and cheaper in their design and construction. Delays and costs of improved mitigation and restoration can result from regulatory barriers. Further, design and engineering costs vary with land ownership, proximity to infrastructure, accessibility, and the level of regulations and risk. This tension reflects the need to expand policy-science conversations, such as collaboration between regulators, the public, managers, politicians, and scientists that has been applied (Ulibarri et al. 2017). For example, project managers in the Columbia River Basin have worked with their legislators to get permission to convert wetlands to build uplands that plants can colonize as sea levels rise.

Recommendation 5. Considering reciprocity of actions through a Tribal ecological and cultural framework will promote climate resiliency.

Reciprocity is a core Indigenous value and a fundamental principle for achieving climate resilience. It is a practice of mutual care and commitment between people and the natural world, as exemplified by the First Foods serving order which reminds us of our promise to care for the Foods in return for their promise to care for us (Quaempts et al. 2018). This principle directly addresses the systemic issues that make ecosystems vulnerable to climate change. Unlike traditional Western management, which has often operated with a one-way, extractive mindset—leading to the over-allocation of water, overharvesting of fish, and excessive greenhouse gas emissions—a reciprocal approach restores balance. It recognizes that relationships, whether interpersonal or ecological, are not sustainable or resilient without mutual care (Quaempts 2025, personal communication).

By embedding reciprocity in climate-resilient restoration, we can:

- **Foster collective responsibility:** Move from individual actions to shared stewardship, where all neighbors linked to a stream or river share the burden of improving it (Trosper 2003).
- **Encourage adaptive learning:** Use management actions as opportunities for continuous learning and adaptation, drawing on the knowledge of both people and the environment itself.
- **Rebuild relationships:** Center the work on trust, respect, and mutual benefit, which is essential for collaborative efforts to address complex climate challenges.

Tribal members practice acts of reciprocity as individuals and are working to apply this principle at a management scale to address historical and ongoing impacts to First Foods resources (Figure 11). By using reciprocity as a guiding principle for fish and wildlife mitigation and restoration, we can build more robust, sustainable, and truly climate-resilient ecosystems.

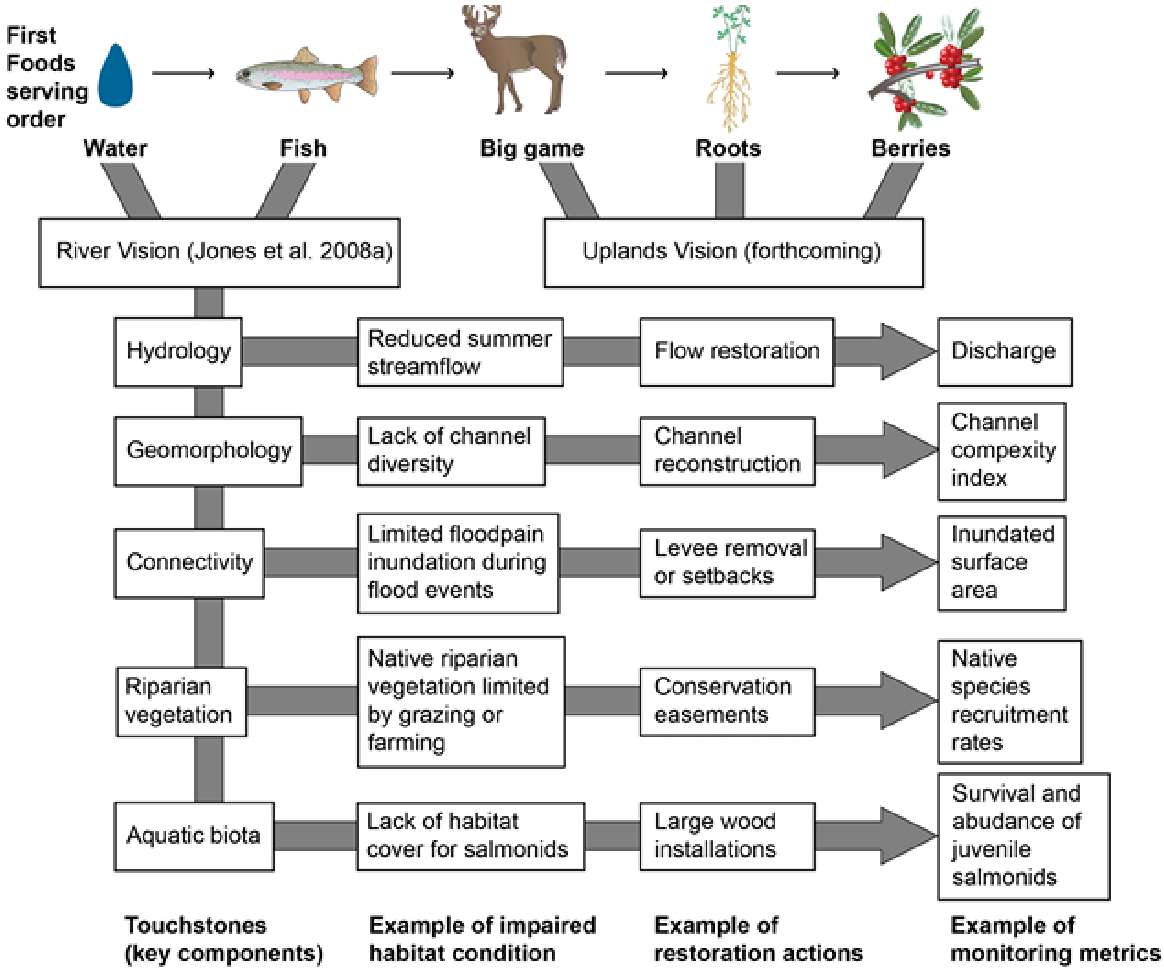

Figure 11. Linkages between First Foods and habitat management (Source: Quaempts et al. 2018). The figure emphasizes the relationships between the First Foods, River and Uplands Visions, and restoration actions and monitoring targets to support recovery of First Foods.

Recommendation 6. Engaging a broader public constituency will increase the scale and benefit of projects.

The need for scientists to effectively communicate with the public through storytelling is more important than ever. Win-win restoration projects are common and result from cooperation among many groups: landowners, funding agencies, recreators, regulators, advocates, and others. These success stories need to be shared within and beyond the river mitigation and restoration community. Furthermore, scientists could better communicate about the uncertain future and risk minimization at a project site with regulators and the public. This takes time and strategic communications, but it allows for bigger projects and greater collective benefits. Some examples of this happening in the Columbia River Basin include:

- Climate curriculum and engagement with youth, such as the activities developed by the Upper Snake River Tribes (Hauser 2025, slides 14-15), represent essential science-education opportunities.
- Innovative partnerships among Tribes, researchers, managers, and the public have helped document and address intersections between food and energy sovereignty, human and ecological health, and carbon emissions (Laumatia 2025, slides 23-24).
- StoryMaps, which are more visually based websites, are particularly effective for communicating landscape-scale concepts to the general public. For example, see the USRT's StoryMap on loss of salmon and steelhead in the Upper Snake River basin (USRT 2023).
- Development of trusted resources for science, project, and policy updates across the basin, such as Columbia Basin Bulletin, is important for disseminating information, including Climate change articles.

Recommendation 7. While some knowledge gaps exist, the current scientific foundation supports taking immediate action toward more climate-resilient restoration.

This report highlights the crucial advancements that have been made in climate change science since 2007, which has significantly closed some important knowledge gaps. Some remaining gaps were identified during the briefings that are limiting climate-resilience planning and action. For example, Crozier (2025) identified some of these research needs specific to salmon, including field-based egg survival studies (e.g., Johnson et al. 2025), examination of carryover effects on subsequent life stages, better understanding of fish disease risks, insights into competition in the ocean, characterization of emerging contaminants and their impacts on aquatic ecosystems, and better models of the factors affecting salmon at sea that go beyond a climate index.

Beyond the briefings, some regional scale processes have contributed to documenting knowledge gaps. For example, some critical uncertainties identified by the ISAB/ISRP in 2016 (ISAB/ISRP 2016-1) are still relevant today, such as:

- How could integrated ecological monitoring be used to determine how climate change affects fish and wildlife and the freshwater, estuarine, ocean, and terrestrial habitats and ecosystems that sustain them?

- What food web effects are associated with long-term climate trends predicted for the Columbia River Basin?

In addition, the ISAB identified two additional knowledge gaps during this review. First, synthesis is needed on where to prioritize research and actions in the Columbia River to best balance cost and results. Rather than generate long lists of everything that is unknown, much of which may not be needed for climate resilience, a synthesis should identify what information is needed to plan, prioritize, and act to save populations. This gap analysis should be led by the scientists and managers directly working with the basin's fish and wildlife who have direct experience with how information gaps limit beneficial actions.

Second, this report emphasized climate-resilience relevant to the salmon life cycle, in part because so much is known about salmon and in part because their status is so discouraging. However, attention is also needed to examine and expand the data on and knowledge of sturgeon, lamprey, and other native fishes. What are their needs and strengths with respect to climate change? What efforts have been undertaken to support them and are they working? Are efforts to benefit salmon helping the other species or not?

However, despite these knowledge gaps, the scientific foundation and existing management principles and tools are adequate to support action towards climate-resilience in the Columbia River Basin.

4.2. Closing Comments

Achieving ecological resilience to changing climatic conditions for an ecosystem as large and diverse as the Columbia River Basin is a complex and enduring endeavor, especially given the legacy of alterations the basin has experienced. Climate change will overlay and amplify impacts to fish and wildlife from other ecosystem stressors, including overfishing, habitat fragmentation and degradation, hydrosystem operations, and spread of non-native species. In short, climate change does not negate the continuing need to restore habitat connectivity and complexity, meet basic ecological flow needs, connect lateral floodplains, deter predators, and other similar actions. It is another anthropogenic disruption to the ecosystem that warrants robust restoration and protection efforts integrated with other ongoing efforts.

Strategies and actions can be (and are being) applied in the basin to address climate change effects. We recommend that such efforts be collaborative, intentional, strategically prioritized, cost-effective, durable, and adaptable. These include continuing to integrate climate change attributes into ecosystem mitigation and prioritization, and the Fish and Wildlife Program, at local watershed to basinwide scales throughout the basin. Fortunately, many tools, approaches, and models are available to assess how climate change fits into mitigation needs. Action-planning can include scenario simulations to test for the responses of the landscape and, ultimately, fish and wildlife, from proposed actions. These planning scenarios will necessitate prioritization of resources and actions that are transparent, equitable, and emphasize reciprocity and dynamic systems. Finally, the methodologies for addressing climate actions are at the leading edge of mitigation and restoration practices. Thus, including an adaptive management loop is critical to evaluate what kinds of actions have measurable benefits to the local conditions and biota.

Appendix: Some best practices for habitat suitability modeling under climate change

Purpose

Development of habitat suitability modeling relies on straightforward methods for model building. Issues like model complexity and how to deal with fish observations that do not include recorded absences in samples (i.e., only presence noted or positive densities reported) are part of the statistical methods and are not covered here because they are well discussed in the literature (e.g., complexity: Merow et al. 2014, Brun et al. 2020, pseudo-absences: Barbet-Massin et al. 2012, Zbinden et al. 2024). Here, we focus on how climate change is incorporated into habitat suitability analysis, including adequate documentation of the methods and proper interpretation of the results. We offer this as guidance for practitioners who apply the habitat suitability models for site-specific actions and as input to broader-scale assessments, as well as an interpretative guide for decision makers, fish and wildlife managers, regulators, and the public who are presented the results of such analyses.

Role of habitat modeling

Habitat suitability modeling is widely used to predict changes in fish habitat under varying or altered environmental conditions (Nestler et al. 2019, Lester et al. 2020). Habitat suitability modeling is an accepted method for assessing how environmental (e.g., temperature, flow), and sometimes ecological conditions (e.g., prey, predators, see Wilcox et al. 2018), combine to affect the quality of habitat. Habitat quality can then affect the growth, reproduction, mortality, and/or movement of individuals of the species of interest. Assessing restoration and management actions under climate change is conceptually a straightforward extension and application of habitat suitability modeling. Explanatory variables (environmental and ecological variables) in the habitat model are typically assumed to remain relevant and exhibit a similar relationship to the dependent variable of suitability under the new conditions expected from climate change. There is also the possibility of adding new versions of already included variables (e.g., extremes, timing, or frequencies of disturbance events) and new variables that become important with climate change. Both modifications would use the same methods as used to develop the original models. The challenges and potential issues are in the details of how this is done and use of the model for novel (never previously observed) conditions expected under climate change. For example, responses of fish to increased temperature might not be simple linear extensions of past observations.

Methods for habitat suitability modeling

Habitat suitability modeling is one approach within a suite of approaches for assessing habitat effects on fish (de Kerckove et al. 2008, Hansen et al. 2024). Habitat suitability modeling is often used alone or with other approaches, such as life cycle modeling, to provide a more complete depiction of both habitat and population abundance responses. Two general classes of habitat suitability modeling have emerged somewhat independently. For convenience, we label these the Expert Opinion School and the Empirical School. Both schools offer useful approaches for assessing how climate change impacts the design and performance of management and restoration actions.

Both modeling schools use the same general framework (Figure A.1). The Expert Opinion School uses laboratory and other data sources, along with expert judgement, to derive a suite of mostly univariate relationships between a scaled response and an explanatory variable (i.e., X axis is the environmental variable and Y axis is zero to one). A spatial grid of 2D cells that cover the area of interest are defined; these cells can be squares with fixed areas or their shapes and areas can vary similar to hydrodynamic and flow models. The spatial resolution and cell shapes of the grid depends on the spatial scale desired for the predictions of habitat suitability; suitability is predicted for each cell. Delineation of vertical layers (i.e., 3D) is a simple extension and is done in larger systems (lakes, ocean) but not often in river and shallow systems.

Each cell is assigned values of the explanatory variables, typically from data or other models, and then the univariate suitabilities (scaled responses between zero and one) are computed for each cell. Figure A.1 shows an illustrative example with temperature, substrate, and presence of shoreline vegetation as explanatory variables (left column). Values of these explanatory variables for each spatial cell are transformed into suitabilities (V_1, V_2, and V_3) and maps of univariates suitabilities can be generated. This is shown as the left-hand y-axis on the plots in the right column and orange lines in Figure A.1. Univariate suitability values are then combined via averaging (typically geometric mean) into a single, scaled habitat suitability index (HSI) score for each cell (bottom map in left column). The spatial and temporal patterns in suitability-scored habitat cells can be examined and compared historically, under different management actions, and with climate change that all affect the values assigned to explanatory variables in each cell. A single metric can also be obtained as the suitability-weighted sum of the areas over all cells.

The Empirical School uses a similar approach to the Expert Opinion School but incorporates survey data on fish and assigns values of the explanatory variables to each catch sample (e.g., presence/absence, catch per effort). The values of explanatory variables are matched to the location and timing of each fish sample either by being measured with the fish sampling or by approximation (interpolation) from data from other surveys or from the outputs from other models (e.g., river temperature). This is shown in the right column of Figure A.1 as the right-hand y-axis (Fitted Response Function) on the explanatory variable plots and the blue lines. Rather than using expert judgement and laboratory results to infer how suitability varies with each explanatory variable, the Empirical School assumes that fish are more likely to be present, or more abundant, in good habitat conditions. Statistical modeling is then used to formulate the habitat suitability model based on how well fish presence or density across sampling locations correlate with the associated explanatory variables. The relationships between suitability and explanatory variables (i.e., Fitted Response Function), analogous to the relationships developed with the Expert Opinion, are then inferred from the fitted statistical model. The same statistical model is used to predict habitat suitability that combines the effects of the explanatory variables.

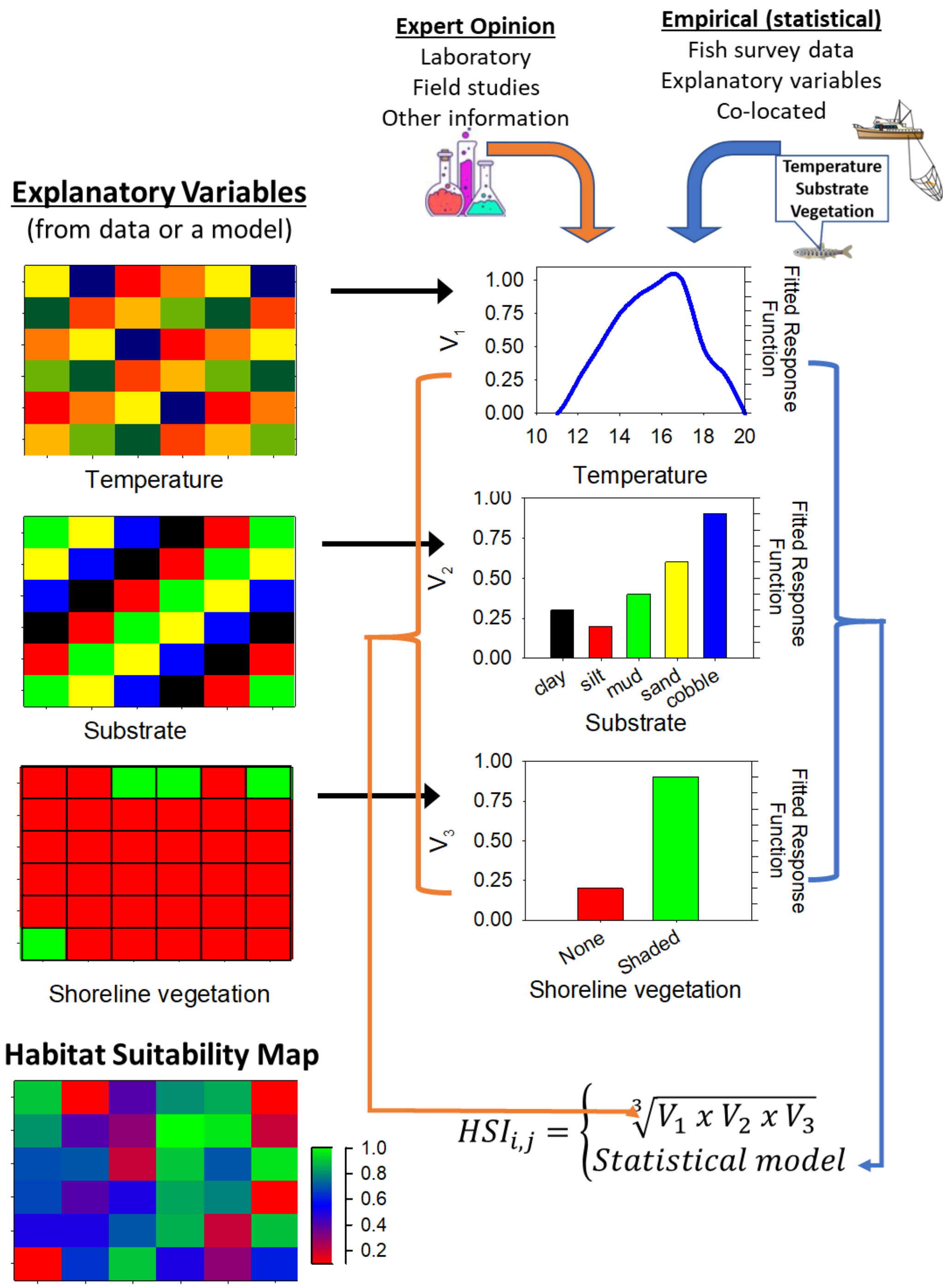

Figure A.1 Schematic representation of the calculations in the Expert Opinion and Empirical Schools of habitat suitability modeling. The habitat suitability model shown is assumed to results from model building and has been validated. The left column shows the explanatory variables as the top 3 plots and the final habitat suitability map at the bottom, and the right column shows the univariate suitability relationships. Each cell of each explanatory variable map is used as input to the univariate suitability relationships. Each cell is scored (0 to 1) (denoted V_1, V_2, and V_3) for the Expert Opinion School (left-side Y-axis, orange arrows) and judged for its influence (Fitted response function) for the Empirical School (right-side Y-axis, blue arrows). Both Schools lead to the final calculation of a habitat suitability index ($HSI_{i,j}$) value for spatial cell. The univariate relationships for the Expert Opinion are based on lab results and other information. The Empirical School fits a statistical model to fish samples that have the values of explanatory variables associated with each sample. The statistical model then can be used to generate the univariate suitability relationships (Fitted Response Functions) and to predict the final suitability ($HSI_{i,j}$) values. Note that the spatial maps of explanatory variables and HSI values are hypothetical and only for illustrative purposes and are not the results of actual habitat suitability analysis.

Empirical School approaches are increasingly associated with the label of Species Distribution Models (SDMs); other labels include environmental niche models and bioclimatic models. Occupancy modeling (MacKenzie et al. 2017) is a variant of SDMs that uses the species' history of detections at multiple locations with explanatory variables to predict the probability of site occupancy (e.g., Young and Carr 2015, Isaak et al. 2022). Robinson et al. (2017) surveyed examples and formulated several best practices for SDMs. Methods for formulating and fitting the Empirical habitat models are well known and tested. Guisan et al. (2017) offered an excellent overview using R, including best practices on model development and its use for projecting habitat conditions under scenarios.

The same explanatory and response variables can be used with both schools, and both schools typically develop a model specific to a species' life stage. The response variable can be the composite (scaled 0 to 1) response, or expected densities obtained by multiplying the scaled response by user-specific maximum densities. Both schools have also been extended by substituting the scaled response with an additional submodel to predict response variables of expected biomass or density of a life stage (e.g., Eastwood et al. 2001, Young and Carr 2015, Jiang et al. 2022), growth, metabolic, and reproduction rates of an individual (Teal et al. 2018), and biomass production rate that combines growth and mortality (e.g., Niklitschek and Secor 2005). The conceptual basis and many of the calculations remain the same as with scaled response variables. The Expert Opinion School has the advantage of great flexibility in which explanatory variables are included and how they are represented. The Empirical School has the advantage of being based on survey data and using well-established statistical methods.

Using habitat suitability as the response variable has advantages as it avoids dealing with the population dynamics (which can be challenging and uncertain) of life cycle modeling, it uses available laboratory or survey data to define the quality of habitat, and it can directly use the outputs from other models such as temperature and flow. Disadvantages include that results are specific to life stages (no link between life stages), are limited to average or snapshot conditions (whereas habitat is dynamic and organisms move), are limited in consideration of trophic interactions, and that the interpretation of habitat suitability as **capacity** for species that may or may not be manifested in the actual in-situ responses in terms of abundance.

Climate change effects to be considered in modeling

The main body of this report summarizes the major effects of climate change on the freshwater and marine (primarily estuarine) environments of fish from the Columbia River Basin. There is a wealth of information on these changes, especially regarding water temperature and flow. Many of the available models and model development methods can, with appropriate care, readily incorporate these changes in variables. These explanatory variables have either already been dealt with for historical conditions or they can be treated in the same way as other included explanatory variables.

Another class of climate change impacts on habitat discussed in the report is more difficult to quantify and for which available habitat modeling tools are less well-developed or are beyond the scope of present habitat modeling. These include how climate change can cause: (1) spatial and temporal changes in sub-daily movement and longer-term migrations that affect how a species uses the habitat, (2) shifts in space-time distributions that change the seasonal matching of prey, predators, and target species and/or food web interactions, which ultimately change how vital rates relate to suitability, (3) uncertain resiliency of habitats that determine their persistence and functionality in a climate change-influenced future, (4) identification of refuge habitats within a dynamic riverscape, and (5) altered connectivity among spatially distributed habitats that determine utilization by individuals. The marine environment will further challenge our ability to predict habitat suitability because changing marine habitats will affect ocean survival and fish distribution and movement.

What to look for in habitat suitability analyses

The list of topics and issues presented below form the basis of a set of best practices. These are synthesized from multiple sources, including: (a) presentations made to the ISAB as part of this review and other ISAB reports on related topics, (b) best practices from papers on habitat and ecological modeling (Heikkinen et al. 2006, Jakeman et al. 2006, 2024, Hirzel and Lay 2008, Swannack et al. 2012, Pickens et al. 2021, Robinson et al. 2017, Rose et al. 2015), (c) a recent paper on how to get bioenergetics modeling of fish growth ready for a changing climate (Rose et al. 2024), (d) discussions as part of the activities of an ICES Working Group on the Value of

Coastal Habitats for Exploited Species (WGVHES[7]), and (e) ongoing efforts as part of the Chesapeake Bay Program to use habitat suitability for guiding (optimizing) management actions to improve the fish and shellfish of the Chesapeake Bay (STAC 2023, Rose et al. 2023).

While the list of sixteen issues and topics appears long, most habitat analyses already address many of them and not all apply to every situation. The key is the documentation of these activities, which often requires relatively brief text that can then be folded into annual or final project reports. We do not discuss best practices related to statistical analyses for habitat modeling, as these are well-documented in other sources (e.g., Guisan et al. 2017). The issues discussed focus on the Expert Opinion and Empirical approaches to SDMs, and most all also apply to related variants such as occupancy modeling. Some of the issues, at a general level, also apply to temperature/flow, life cycle, and movement modeling. These include: (a) defining the questions (Issue 1), (b) use of conceptual models (Issue 4), (c) version control (Issue 7), (d) specifying baseline and scenarios and designing simulation experiments (Issue 8), (e) performing model validation (Issue 10), (f) ensuring transparency (Issue 11), (6) considering stochasticity and uncertainties (Issues 13 and 14), and (g) effective communication and post-auditing (Issues 15 and 16).

1. ***The questions are clearly stated and testable, and answers are formatted for easy uptake by management.***

Defining the questions is a critical step in ensuring the modeling results will be reported, used, and remain relevant long after their initial generation. Consideration of climate change adds another layer of complexity to formulating testable questions. Often, modeling does not have its full impact on management decisions because of the lack of specification of the questions to be answered, coupled with people having overly high expectations of what the modeling can do.

The more specific the questions, the more likely a model can be configured and simulations designed to answer them. A hypothetical illustration of poorly and well-stated questions would be: (1) What are the effects of increased spawning habitat on reproduction, versus (2) How does increasing the areal extent of existing spawning area by 50% by adding cobble (20-75 mm) and gravel (3-25 mm) affect salmon embryo survival? Key features of testable questions are an explicit statement of directionality and magnitude of the response, and when possible, a rationale about proposed causative and alternative mechanisms (e.g., other stressors, high flow events redistributed the added cobble/gravel outside of spawning area) that explain why the response is

[7] ISAB member Kenny Rose is also a member of the ICES Working Group on the Value of Coastal Habitats for Exploited Species.

expected. Often, these alternative mechanisms can be explicitly modeled as part of sensitivity or uncertainty analyses.

The term “habitat” is often used in a vague way without explicit definition, leading to ambiguity and misunderstandings (Bamford and Calver 2014). Whenever the term “habitat” is used, its link to the key features of the habitat that relate to vital rates of individuals (e.g., growth, mortality, reproduction) should be specified to ensure well-posed questions and effective communication.

2. ***The rationale for using habitat suitability as the primary response variable is provided.***

It is important to provide the rationale for using habitat suitability (or some direct measure of fish presence, abundance, or vital rate) as the response variable, so managers and stakeholders know this decision was thoughtful and alternatives were considered. Population abundance or population-level survival (e.g., SARs) are, at least conceptually, easier for managers and the stakeholders to interpret. There are many reasons to use population-level abundance and survival but also many situations for which habitat suitability is a better predictor. A common situation that justifies using habitat suitability is when the information needed to estimate abundance or survival is too limiting (i.e., predicted values of abundance and survival have too much uncertainty).

Growth rate potential is how an individual would grow in body size in response to environmental conditions and food access if it inhabited a particular location. Using potential growth rate as the response variable is a relatively easy extension of habitat modeling that is rooted in physiology, and growth rate is one of the key vital rates related to population dynamics (Robinson et al. 2017, Teal et al. 2018, Rossi et al. 2024). We have a good understanding of climate change effects on fish growth rate (Huang et al. 2021, Reeder et al. 2021) and subsequent effects on life-cycle events such as smolting and maturation (Thorpe 2007, Thorpe et al. 1998, Benjamin et al. 2013). Assessing the resiliency of the habitat and the connectivity of habitats for management actions is important but challenging and especially so under climate change (Bouska et al. 2019, Yang et al. 2024, Hansen et al. 2023). Several models for assessing connectivity applicable to the Columbia Basin are available (ERTG 2022). Resiliency is conceptually understood, but quantification is still being refined (Angeler and Allen 2016, Baho et al. 2017, Tracy et al. 2022). Resiliency is a critical aspect of the strategic-level climate change vulnerability assessments (see main report). One basic approach for quantitatively assessing resiliency of habitat is to use habitat suitability and life cycle modeling to determine if the habitat will continue to function as designed under projected future conditions (e.g., 2050, 2100) (e.g., Beechie presentation to the ISAB, Isaak et al. 2015, 2022).

3. ***Relevant available data and information (e.g., laboratory studies) have been assembled, and survey data are organized in a proper database.***

Habitat suitability modeling involves a switch in the spatial reference system of the analysis from geographic space (e.g., latitude-longitude) to habitat space (e.g., temperature-flow). A two-year spatially detailed study with co-measured explanatory variables might be better for habitat suitability modeling than decades of observations at a few stations or survey data that requires extensive geo-referencing and time-matching of environmental data. Emerging data sources that can generate detailed spatial coverage are new sampling methods for detection (e.g., eDNA, Young et al. 2022) and open-source (and often crowd-sourced) datasets of geo-referenced potential explanatory variables derived from models or remote sensing (Isaak et al. 2018b). Often, people reply when asked about the availability of data "that survey was only a few years" and "we do not have long-term data." Whereas the switch from geographic to habitat space means spatially detailed data is more important than long time series. Both the Expert Opinion and Empirical schools use laboratory and field experiments, and they should be documented in terms of how they were originally collected and how they were used to inform the habitat suitability modeling.

Readily available software packages can provide search and retrieve capabilities, meta-data documentation, and version and security controls. Reliance on multiple Excel spreadsheets, maintained independently by multiple investigators, should be avoided.

4. ***A conceptual model (or table of hypotheses) is presented that shows how the key factors, stressors, management actions, and climate change affect habitat, and how habitat affects presence, abundance, and/or vital rates of targeted biota.***

In suitable and accessible habitat, four fundamental processes affect the abundance of salmonids and other species: 1) growth affects size of individuals, 2) mortality affects numbers of individuals, 3) reproduction affects numbers, and 4) movement affects the locations of individuals. Growth is important to abundance because mortality and reproduction are often based on size. Movement is important because most species have one or more life stages that disperse via passive transport or active movement, which affects the habitat, predators, prey, and environmental conditions experienced by the individuals and hence their growth, mortality, and reproductive rates.

Conceptual models are an important communication tool for explaining what was considered important and included in the modeling (Ogden et al. 2005, DiGennaro et al. 2012, Argent et al. 2016). Conceptual models should include graphical representations and explanatory narrative. They should specify what factors (e.g., temperature, prey) are considered important and the cause-and-effect relationships between these factors and the growth, mortality, reproduction, and movement of the target species. The conceptual model should not be limited to the variables included in the model but should show all factors thought to be important. Those included in the model selected can then be highlighted in the conceptual model. The conceptual model should also show how management actions and climate change are envisioned as affecting the vital rates.

Management actions and climate change can affect the existing (historically based) relationships (e.g., earlier migration), as well as generate new relationships (e.g., greater importance of invasive species that could have been previously ignored). Care must be taken to describe whether representation of these environmental and biological factors will be explicit or implicit in the habitat suitability model. Explicit representation means the specific effect is an actual term in the model that can be adjusted. Many habitat effects not stated in a model can still be assessed if the effect does not appear in the model. First, one determines how the effect of interest influences variables already in the model and then varies those variables the appropriate amounts (Lipcius et al. 2019). For example, a model predicting abundances using reproduction and survival can be used to assess how changes in individual growth rates would affect population abundance. Growth can be used to change the fraction mature or fecundity by age schedules and body size can be used via susceptibility to predation to adjust the mortality rate.

The conceptual model should include a life cycle diagram and space-time plots for broader perspective. A life cycle diagram follows individuals as they progress through the life stages from birth to death (Caswell 2001). Life history patterns are determined by the combination of vital rates with the life cycle, determining how individuals progress through their life cycle. The life cycle shows how changes in other life stages can influence the responses of the life stage of focus. Space-time plots show how individuals use the various habitats within the year as they advance through their life cycle.

The conceptual model should also include the temporal and spatial scales of the explanatory variables, and the important hidden assumptions should be stated. How environmental conditions will be considered (e.g., averaged, maximum) over time (e.g., daily, monthly) and space (grid) for habitat modeling for the life stage is important for the conceptual model. The explicit assumptions with habitat suitability models are well described; e.g., the system is at equilibrium, the fish data were collected with minimal bias, and the explanatory variables were measured without error. With climate change, examples of additional (“hidden”) assumptions that are rarely mentioned or briefly noted include: (1) how plasticity, acclimation, adaptation, and phenotypic variation would affect the suitability of habitats, (2) sensitivity of predictions to alternative assumed or downscaled climate change conditions, and (3) possibility of changes in the physical structure and food web of the system.

5. ***A systematic process was used to identify candidate models and select the final model(s).***

Often one cannot identify the best model with absolute certainty. With Expert Opinion, documentation of the selected model is especially difficult and requires a thorough explanation of what information was examined, what was used, and how different lines of evidence were combined into the suitability functions. The documentation of the Level 2 variables in EDT illustrates such a process. It is easier with Empirical models because the practitioner can rely on the availability of data and statistical theory (e.g., AIC or BIC). However, it is often the case that alternative versions of the model appear ranked, but they are actually very close to each other based on the ranking statistic. The selection of a "best" model is important as the entire analysis will be predicated on the model selected and careful attention to the model selection process positions the practitioner and users to be able to later explain and rationalize the model used and the results it generated.

Two approaches to dealing with similarly ranked alternative models are: 1) compare the candidate models to other models in similar situations or 2) use a multiple model or ensemble approach. Too often, the fitted habitat models are presented in isolation. By comparing the model(s) to other analyses reflecting the opinions of other experts who may have used different data and model building approaches, one can view the candidate models in a broader context for confirmation or questioning. This helps in synthesis of results across different analyses, needed when combining projects at the basin level.

The second approach of multiple or ensemble modeling is more formal and keeps the alternative models throughout the analysis (e.g., Lin et al. 2015). A multiple-model approach can effectively quantify the level of uncertainty of predicted responses to alternative model formulations and are increasingly being used in many fields of modeling. In concept, each model represents a different (but plausible) view of the real system. When predicted responses of multiple models agree, uncertainty is reduced, increasing confidence in the model results. Disagreements among models are also useful because they show a range of possible responses that are plausible. Several impacts from climate change (invasives, droughts, heat waves) can create novel conditions that can most effectively be addressed with multiple alternative models. Any assessment that involves multiple analyses needs a plan for how to integrate the results so that synthesized information can be leveraged beyond a simple collection of independent analyses.

6. ***Why certain explanatory variables were included and others omitted in the analyses is explained.***

Clear explanation of the explanatory variables included and those omitted preempts questions from managers and stakeholders about "missing variables." Were explanatory variables not included because they were deemed unimportant, because they were simply not available to evaluate for inclusion, or their effects better represented with other variables? The covariance among explanatory variables should also be reported. Sometimes a single statistical model is identified and used, but omitted explanatory variables were correlated with other variables and were just slightly less informative. The discussion should relate the variables and factors shown in the conceptual model with the actual variables included in the habitat model. An omitted variable may be more appropriate for representing climate change and for informing habitat design and management than the included variable.

The realism of the shape and magnitude changes of the univariate relationships should be documented. These would be plots of the suitability values versus each explanatory variable. If there are interaction effects, then these should be shown as well. For example, if the effect of temperature and substrate type on suitability included an interaction, then this should be displayed graphically.

All analyses must include explanatory variables important to the response variable and not be limited to only climate change or management-relevant variables. This is to try to minimize the "error term" and allow for more power to compare among scenarios. For example, if one left out temperature from the model and it was important, then the predicted response variable would have inflated variability (error), making isolation of the response attributable to the management action more difficult. Climate change and design of habitat restoration also require that the explanatory variables include variables that can become important in the future and include management variables that allow for specification of alternative restoration designs.

Often, when designing habitat restoration or using the models for previously unobserved conditions (e.g., climate change), a hybrid version for habitat modeling that combines Expert Opinion and Empirical approaches is likely needed. Both schools can often result in models that do not necessarily include all of the explanatory variables needed. In addition, variables may change their relationship to suitability because studies did not consider extremes or the combinations of stressors expected in the novel conditions. Similarly, new variables not previously considered important may become important under the new conditions. Hybrid versions that combine laboratory data/expert opinion or add not-statistically significant explanatory variables into models remain an area of active research.

7. ***Version control of the data, models, and results is explicitly described.***

Habitat suitability modeling, like population and ecological modeling in general, is an iterative process, involves extensive updating of files, and multiple investigators. File transfer among investigators can often lead to problems and errors. Further, results are provided, and decisions can occur months to years later, sometimes requiring modifications to the model based on new information and updating of the model and data. Transfer of Excel spreadsheets among group members should be avoided. A protocol for keeping track of input files, model versions, data, and results is needed to ensure reproducibility of analyses and keep everyone using the correct versions of files and data. Record-keeping is a standard part of the scientific method, but habitat suitability analysis requires an especially rigorous set of protocols because the analysis can span multiple years and typically involves multiple datasets, models, and investigators.

8. ***Baseline or reference conditions are rationalized and well-documented.***

There will always be some type of baseline or reference condition against which the effects of climate change and management/restoration actions will be compared. Typically, the baseline is the current condition or some form of "future without action." Defining reference or baseline conditions in a system that has undergone major environmental changes is challenging (Duarte et al. 2009, Balaguer et al. 2014, Guerrero-Gatica et al. 2019). With the addition of climate change, the baseline or reference condition can be presented with and without climate change. The baseline needs to be explicitly defined, and a rationale provided, and definition of baseline and scenario conditions should follow a specified process (Metzger et al. 2017).

Ideally, analyses are designed so that comparisons only differ by whether the project or action are included. Scenarios are then defined relative to the baseline and baseline plus climate change. Restoration often does not result in functionality of habitats simply reversing their state along the historical trajectory. The analyses to evaluate scenarios should be treated as rigorously as one designs a laboratory experiment (Kleijnen 2018). The design used (e.g., factorial, regression-like) should clearly state the treatments and their levels, the confounding factors, and how the combinations will be compared. Climate change can be viewed as a confounding factor but also can be considered, like the management action, as a treatment in the simulation experiment. An explicit design that treats the action (without and with) and climate change (present-day and future) as treatments allows for predictions for all four combinations of:

A. present-day without project and without climate change (baseline or control),
B. present-day with project but no climate change,
C. present-day without project but with climate change (i.e., future without project), and
D. present-day with both project and climate (i.e., future with project).

These four combinations enable isolation of the effects of the action without climate change (B versus A) and with climate change (D versus C) and quantification of the effects of climate change on baseline (C versus A) and the action (D versus B).

There are several approaches to generating plausible future conditions under climate change. The Delta Method is based on the simple manipulation of historical conditions (e.g., +2°, 1.5 x river flow). While intuitive and useful for exploratory analyses, this method fails to realistically represent the effects of climate change such as more extreme floods or more frequent floods. A second approach is to select a subset of historical year(s) that resemble future conditions. There may be several warm years with earlier and increased precipitation or snowmelt, and these can be used to represent a climate change future. A third approach is to use downscaled climate scenarios from Global Circulation Models (Hamlet et al. 2013, Rana and Moradkhani 2016, Rupp et al. 2017, Marshall and Lute 2022), so they are localized enough to input directly into the habitat modeling analysis or first inputted into local/regional hydrodynamic models or temperature/flow models and those outputs used as inputs to habitat models.

9. ***Careful consideration and explanation of co-locating and time-matching of variables and dimension reductions.***

With the Empirical approach, an important step is how explanatory variables obtained from sources other than the fish survey are assigned to fish samples (Nunez-Riboni et al. 2021). The challenge is usually overcome with interpolation and extrapolation methods, which can get complicated when both space and time-matching with the samples is required. This is critical as the assumption is that the assigned values to a sample reflect what the fish was reacting to. With the Expert Opinion approach a similar challenge is how well do the explanatory variables used to populate the grid (often with resolution of 10s of meters) reflect the habitat experienced by the fish.

There is a strong tendency to focus on the values of explanatory variables for habitat modeling averaged over time periods and/or spatial cells. The rationale for averaging should be provided and also consider other statistics of explanatory variables, such as maximum, minimum, and variance, as important information to pass from climate change impacts to the habitat models. Hatten et al. (2009) determined that including the degree of stability and persistence of hourly water velocities were important to characterizing the suitability of spawning habitat. Vasseur et al. (2014) illustrated in a general situation the importance of including the variance of temperature to the physiological response of fish. They assumed climate change not only caused an increase in the mean temperature but also affected the variance around these means. Different variances with the same increase in the mean temperature greatly affected the physiological performance (typical of a growth rate relationship with temperature) when integrated over individuals starting at different temperatures. Dimension reductions of explanatory variables is critical and a wide range of possible ways to characterize the variables (e.g., extremes, variability, stability) in addition to the mean should be considered.

10. Validation strategy is described, and results are documented.

Validation is what many managers and stakeholders use to determine if they trust the model results, though the term itself has been discussed for decades (Barlas and Carpenter 1990, Refsgaard and Henriksen, 2004 Rykiel 1996). Wainwright and Mulligan (2013) offer a good list of ways to validate models. Validation involves the testing of model behavior and predictions with data not used in the model's set-up (Expert Opinion) or its calibration (Empirical). Expert Opinion models can use survey data for validation (more fish should be found in higher quality habitat). Empirical models use the survey data to fit the model, and so the concept of out-of-sample or split conditions (which must be contrasting) is typically used to validate Empirical habitat models. With the rise of individual-based modeling, the idea of pattern matching (Grimm et al. 2005) over goodness-of-fit statistics based on predicted versus observed has also gained traction.

The challenge to validation is that habitat suitability as an entity is not observed in nature, and the effects of climate change and the proposed management and restoration actions have not been observed yet. Thus, non-traditional approaches to validation are needed.

One possibility is the "divide and conquer" approach (Lorscheid and Meyer 2016). "Divide and conquer" uses designed simulation experiments that evaluate the performance of individual modules and then perform additional simulation experiments that allow assessment of the behavior of the full model. For habitat modeling, this can be testing using extreme conditions of performance of each of the univariate suitability function and then testing various combinations with the full habitat model. Extremes of the explanatory variables can be defined by the climate change scenarios and the management actions combined with extremes in natural conditions.

Another validation strategy can also make use of observed extreme conditions (Tommasi et al. 2017, Becker et al. 2019, Harris et al. 2018). Rather than the traditional mindset of focusing on model performance on its agreement with long-term average conditions or how the model fits many years of the observations, the historical data can be partitioned to allow testing for extreme conditions that may push model evaluation closer to the anticipated novel conditions expected under climate change. For example, exceptionally warm years can be simulated in sequence, or years with extended heatwaves (Smith et al. 2023) can provide data for model testing of possible responses to warming. Using an analogous approach, one can substitute space for time and compare model predictions using observed distributions in nearby systems that already show the future conditions expected in the system of interest.

11. The modeling effort is sufficiently transparent.

Openness and transparency are both important concepts to ensure clarity in the reporting of the methods and results to managers and the public. Openness means the data and codes are made available, while transparency goes further and documents why decisions were made and how results were interpreted. While related, openness is not equivalent to transparency. Openness can be achieved by simply making everything available. This can, in some situations of massive documents, files, and codes, actually counter transparency. There are standards for sharing models (Ketternring et al. 2006) and open science (Hampton et al. 2015, Powers and Hampton 2019). Manager and stakeholder engagement and decision support tools can contribute to transparency by formalizing and clarifying the modeling-related decision process (McIntosh et al. 2011, Walling and Vaneeckhaute 2020). Both an open process and transparency are needed.

12. Reporting of the expected time scales of habitat and fish responses.

Habitat modeling is fundamentally based on equilibrium assumptions (Guisan et al. 2017). This is needed for fitting to survey data and for the suitability relationships to be combined. Thus, habitat modeling does not generate information about response times. Some management actions or restored habitats cascade through vital rates quickly, while others involve lags in responses because the habitats require years to become fully functional, fully utilized by organisms, and effects realized. In many applications, the ultimate response of interest is at the population-level, which is an annual or even decadal scale response. Some discussion of response times, appropriately explained and caveated, should accompany the habitat analyses.

13. Uncertainties, certainties, and stochasticity should be distinguished and documented.

Different sources of variability in data and models require proper interpretation for the results to be used effectively for management (Regan et al. 2002, Link et al. 2012). In general, if more measurements reduce variability, then one deals with uncertainty, whereas when more measurements do not reduce the variability, one deals with stochasticity (Ferson and Ginzburg 1996). Dealing with lumped and vague terms like “variability” or “uncertainty” without specific definitions reduces our ability to interpret and communicate the results.

Link et al. (2012) discussed sources of variability in the use of models for managing living resources. They reviewed the extensive literature on uncertainty and delineated six types when using models to inform management: (1) natural variability (same as stochasticity above), (2) observational error that arises from finite sampling (frequency, specific locations) of the complex ecosystem such that the data differ from truth (which is not observable; Stow et al. 2009), (3) inability to determine the optimal structural complexity of models, (4) inadequate communication of results to various audiences, (5) unclear management objectives and vaguely stated questions to answer, and (6) outcome uncertainty due to responses to the actual implementation of the management differ from the *a priori* management goals. All modeling related to assessing the responses of living resources to management actions, including habitat modeling, must carefully consider all these sources.

14. Sensitivity and uncertainty analysis

Sensitivity and uncertainty analyses are often confused. Sensitivity analysis refers to model responses to uniformly-applied small changes in explanatory variables, while uncertainty analyses use realistic changes in explanatory variables. Uncertainty analysis is directly useful to management because, if done correctly, it reveals the variability of predictions expected to occur in nature. The methods used can be the same for both types of analyses and determining the realistic variability in variables and any covariances should be documented (see Cariboni et al. 2007, Pianosi et al. 2016, Steel et al. 2009).

The broader issue is that all models will be sensitive to some inputs relative to others, and all will or can generate predictions with uncertainty but interpreting the resulting variability can be problematic. It is easy to use the idea of sensitivity and uncertainty analysis to somehow foster additional confidence in the model predictions when, in fact, the analyses are often misinterpreted and do not result in any changes to the model. Climate change adds another layer of uncertainty to the modeling analyses in terms of the expected changes in the environmental conditions going into the future and needs to be included in sensitivity and uncertainty analyses. When used appropriately and when the explanatory variables and parameters are carefully considered and documented, sensitivity and uncertainty analyses are very useful for refining the model and interpreting model predictions to inform management decisions.

15. Guidance on interpretation of modeling results is provided.

Guidelines for interpreting habitat modeling results should accompany each project and be updated as the modeling progresses. This includes measures of the appropriate levels of confidence appropriate to the different predictions. Such an interpretative guide can distinguish among the different audiences that receive the results: other practitioners, managers and regulators, informed stakeholders, and the general public. Effective techniques for describing the methods and presenting the results of complicated model analyses are available (Grimm et al. 2014), and there are science communication concepts for technical and general audiences (Schmolke et al. 2010, Chagaris et al. 2019, Peterman 2004, Nisbet and Scheufele 2009). Schuwirth et al. (2019) offer some best practices on communicating modeling results to inform management decisions.

Two issues that often deserve more attention are: (1) adequate documentation of uncertainties, including what aspects of the results have high confidence (certainties), and (2) explicitly displaying tradeoffs. Tradeoffs are common in management actions and restoration, including whether to sacrifice some benefits of a species to obtain greater benefits for another species or when some undesirable species (e.g., invasive) may benefit from improvements in habitat. Also, inferior habitat for one species is not a biological desert. Restoration often involves creating vegetative habitat that removes open-water habitat; open water is high quality habitat for other species.

16. A post-audit is planned or performed.

Post-auditing is documenting the model in its final form, reporting how it developed (what was considered) throughout the analysis and revisiting some of the major steps to ensure all information is up to date. Post-auditing is a combination of archiving and back-checking to see if any new data are available or if the conceptual models have changed based on new information. Some regulatory processes take years, then there is a hiatus period, and then the question arises again. Post-auditing is extremely valuable when modeling results need to be revisited or to maintain consistency across projects, so others know what model and approach were used.

There should be a plan for code management, model inputs and outputs documentation and storage, and data exchange protocols. Key personnel will likely leave, and models will likely continue to need to be updated. Legacy planning is needed to ensure the analyses are repeatable, can be easily used as the basis for subsequent analyses, and can be used and updated for validation using post-implementation monitoring.

Concluding remarks

Habitat suitability modeling is an important tool for predicting changes in fish habitat quality and quantity for management actions and restoration under climate change. Such models can vary in their integration of expert opinion and empirical data on fish occurrence and density. Regardless of this distinction, model developers should follow best practices to ensure maximum value and usefulness. The suite of sixteen best practices presented here relate to model planning, implementation and testing, and communication and documentation.

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