Columbia River salmon and steelhead in an ecosystem based management framework: Partnership and collaboration building

Report from NOAA to the Columbia Basin Task Force in response to the Resilient Columbia Basin Agreement

January 17, 2025

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1.0 Introduction

Background

The Six Sovereigns' 2023 *Columbia Basin Restoration Initiative* (CBRI) outlines a durable long-term strategy to restore salmon and other native fish populations to healthy and abundant levels, ensure a clean energy future, support local and regional economic resilience, restore ecosystem function, and honor commitments to Tribal Nations. The CBRI drew on the September 2022 *Rebuilding Interior Columbia Basin Salmon and Steelhead* (NOAA's Rebuilding Report). The Rebuilding Report built off the Columbia Basin Partnership (CBP) goals and objectives for rebuilding salmon and steelhead populations, as well as decades of converging collaborative science pointing to the urgency of addressing life-cycle impacts of the hydro-system and other limiting factors in the face of climate change.

The Columbia Basin Partnership (CBP) was a Task Force chartered by NOAA's Marine Fisheries Advisory Committee in 2017 to develop a common vision and goals for the Columbia River Basin's salmon and steelhead. CBP members included tribal and state sovereigns and a diverse suite of regional stakeholder groups, representing ports, electric utilities, local watershed recovery, irrigators, agriculture, sport fishing, commercial fishing, and more. The CBP examined the science and history of salmon in the region and developed a common vision and qualitative and quantitative goals that went beyond achieving Endangered Species Act (ESA) delisting levels to rebuild healthy and harvestable runs of all salmon and steelhead stocks that would restore the economic, ecological, and cultural benefits the region wants from the Columbia River Basin. While the CBP did not include potential actions in the marine environment, nor in response to broadscale climate change, the CBP members, nonetheless, unanimously agreed that urgent and immediate action is possible, and required. The CBP members concluded that to achieve their regional vision and goals for salmon and steelhead, bold actions would be needed to address the full range of threats that the species face. Furthermore, they noted that reliable and predictable funding for these actions would be essential.

Ocean and Estuary Research and Management Commitment

As part of the court mediated stay in litigation[1], a "Resilient Columbia Basin Agreement" (RCBA) was developed between the US Government and the six sovereign litigation parties, that included, among other components, a Memorandum of Understanding and a list of U.S. Government Commitments in Support of the "Columbia Basin Restoration Initiative". Under the RCBA, the United States Government committed to work with the Six Sovereigns through a whole of government approach to develop further actions. Through the RCBA, NOAA has committed to actions that support the ecosystem science used to inform and guide conservation and management decision-making. These ongoing actions will build on the CBP's foundation, in

[1] National Wildlife Federation v. National Marine Fisheries Service, 3:01-cv-640-SI (D. Or.) (NWF v. NMFS), Pacific Coast Federation of Fishermen's Associations v. Bonneville Power Administration, 20-73761 (9th Cir.) (PCFFA v. BPA), Coeur d'Alene Tribe v. Bonneville Power Administration, 20-73762 (9th Cir.), and Spokane Tribe of Indians v. Bonneville Power Administration, 20-73775 (9th Cir.)

particular, building from and adding to the information base represented by the CBP Phase 2 report. While the CBP Phase 2 report represents the culmination of many years of work by a large and dedicated team, as noted above, the CBP chose not to address salmon ocean ecology and the potential impacts of climate change as these sectors were not directly controllable by partners' actions. As such, NOAA's expertise and capacity in marine and estuary salmon ecology and life-cycle projections of climate change impacts represents an ideal opportunity to collaboratively advance the CBP's work.

Under the RCBA, NOAA committed to prioritize ongoing work to develop decision support tools to track ocean productivity in a stock specific manner and to develop indicators that provide valuation for nearshore, estuary, and tributary habitat that can be used for restoration planning and prioritization. NOAA also committed to collaborate with sovereign fish managers and regional entities conducting fisheries research in marine environments to:

- Identify mechanisms and tools for lifecycle modeling, monitoring, and adaptive management efforts to better integrate new information on ocean conditions and marine fish survival as it becomes available; and
- Identify management information gaps where expanded ocean research could support improved adaptive management of US Government's Commitments in response to the CBRI.

This report is based on ongoing ocean and estuary salmon research in the NWFSC portfolio; in particular, work currently used to develop lifecycle survival based decision support tools. The report also identifies gaps in our knowledge and research activities that are thought to be critical to a more complete understanding of marine physical and biological processes. In light of our current knowledge base and our understanding of salmon and ocean ecology, the report identifies example management actions and strategies that could be explored by research and manager partnerships. It also highlights risks and opportunities. The report also offers suggestions for a collaborative framework to further develop salmon and steelhead rebuilding opportunities across ocean and estuary ecosystems and leverage these opportunities to learn and act in a co-stewardship manner.

The report recognizes that the need for and importance of gaining a better understanding of marine and estuarine dynamics and impacts on salmon survival is an opportunity for regional collaboration and partnership. Key regional partners and resource co-stewards have ongoing research and management programs that can strengthen NOAA's capacity for supporting ecosystem based fisheries management of Columbia River salmon and steelhead stocks. Importantly, the report acknowledges information and data gaps, but in the context of the full salmon lifecycle (e.g., carry over impacts from freshwater conditions), as potential arenas for adaptive management actions (e.g., implementing management experiments), and as a critically important setting to illustrate where a precautionary approach is not to be conflated with a no-action path.

Objective

Summarize the state of our knowledge and the ongoing NWFSC research efforts around ocean and estuary ecosystems from a lifecycle survival perspective for Columbia River salmon and steelhead, including identifying key gaps in information, carryover effects from freshwater conditions and experience, as well as potential management actions areas that our current knowledge and research suggest. Finally, to advance Columbia River salmon and steelhead rebuilding and recovery, identify a collaborative structure to guide strategic planning for management action design and implementation that adopts an ecosystem based fisheries management paradigm.

Next steps

With the regional sovereign fishery managers and treaty rights holders, we will to co-produce a more fully complete knowledge base and gaps identification process in the arena of ocean and estuary salmon ecology, including specifying where actions can be taken now and identifying tools for decision support that would improve the efficacy of future conservation and management actions. To make progress in this direction, the following specific components will be necessary.

- Develop guidelines for collaborations, interactions, and knowledge co-production that can inform our research and co-stewardship communities. Including, supporting existing and developing new, as needed, collaboration and knowledge co-production settings to foster effective interactions (e.g., NPCC Ocean Forum).

- Develop a shared strategy for identifying knowledge and information gaps, constraints on addressing gaps, and solutions for moving the Columbia River basin community forward in a productive, collaborative manner.

- Develop an ocean-estuary salmon ecology research plan. The plan would be a strategic action plan to improve recovery and rebuilding science and management decision making support in the arena of ocean-estuary salmon ecology, with a particular focus on developing decision support systems and necessary monitoring to guide conservation and management actions that maximize return on investment.

- Develop a decision support system based on lifecycle models (LCMs) developed by the research community. Using LCMs allows the strategic plan to be dynamic, in that the models can incorporate and integrate new information, generating updated predictions of management action impacts. Similarly, the LCMs allow for rich scenario evaluations, thereby developing action plan alternatives with initial risk and benefit estimates.

- Collaboratively develop management scenario evaluation tasks for the decision support system and action plan implementation design. Candidate high priority scenarios from current knowledge include:

- Reducing carryover effects for salmon entering the ocean by increasing tributary and mainstem riparian and floodplain restoration actions to improve smolt body size and run timing.
- Manage spill at mainstem dams and restore migration corridors to reduce migration corridor carryover effects.
- Increasing estuary restoration. Estuary restoration improves salmon prey availability and reduces predation by providing alternative food sources.
- Coordinate with fishery managers on Fishery Management Plans for coastal pelagic species. Increasing forage fish can provide an alternate prey for salmon predators which increases salmon survival.
- Coordinate regional hatchery and harvest management with ecosystem status forecasts to improve overall ocean/estuary food webs.

2.0 Current knowledge supporting ecosystem based fisheries management

Salmon and steelhead are keystone species for the culture and economy of the Pacific Northwest. Societal and religious icons of the region and its peoples, salmon and steelhead are critical to the identity of salmon country (USFWS 2024). Once abundant in nearly all of the streams, rivers, lakes, and estuaries of the northern pacific and atlantic coasts, salmon and steelhead worldwide have declined dramatically due to development and exploitation. Along the US Pacific coast, the historically low run sizes of these fishes has resulted in a generation of action, from harvest restrictions, to regulatory controls on land and water use, to stream and estuary restoration, to conservation hatcheries and captive breeding programs. This action ecosystem is underlain by a rapidly expanding knowledge base that guides and adjusts regional programs and initiatives. Despite the extensive efforts of managers, researchers, regulators, and society as a whole, a conservation status remains warranted for the majority of salmon and steelhead populations along the Pacific coast (NOAA 2024).

Salmon and steelhead populations and habitat are economically important to people throughout the Columbia River basin. Populations and habitat for these iconic fish are important for three reasons. Decisions regarding the management of salmon populations and salmon habitat can increase individual and household income. These decisions can differentially influence the cost of living for households. And lastly, these decisions can influence the economic wellbeing of municipalities and communities. Some effects are monetary; however, many of the most important do not directly translate to money. We have learned for example that recreationists assign a much greater value to a fishing opportunity than they actually spend for a day on the water (Rosenberger 2023). The economic importance of non-market benefits from healthy salmon and steelhead populations influences the location of households and businesses, diversifying and adding economic strength to communities no longer dependent on extractive industries. Overall, it is critical that when considering the societal impacts of salmon and steelhead rebuilding and recovery, that we consider all stakeholders, current, future and historical.

Salmon and steelhead lifecycles require access to thousands of miles of freshwater habitat, functional estuaries and nearshore marine environments, and the entirety of the north east Pacific Ocean. The ecosystem footprint of Columbia River salmon and steelhead is spatially vast, and structurally complex, depending on and supporting multiple foodwebs in freshwater, estuarine, and marine environments. With a generation time of 3 to 10 years, reproductive strategies must buffer for climatic fluctuations that differentially impact all lifestages. Salmon and steelhead have evolved to thrive within this lifecycle challenge, and as a result are remarkably adaptive and resilient. However, a century of anthropogenic simplifications and reductions in productivity of freshwater and marine ecosystems have lowered the overall productivity of Pacific salmon and steelhead populations, as well as their life history diversity, and as such, their resilience and capacity to respond to further reductions in environmental conditions. NOAA Fisheries is charged with supporting the conservation and management of these living marine resources, and to do so, applies the principles and practices of Ecosystem Based Fisheries Management (EBFM).

To fully implement EBFM for the salmon and steelhead of the Columbia River basin, the regional co-managers and co-stewards of this resource need to reconcile the competing demands directly on the fishery resource itself with the indirect demands on the natural resource base that supports the fishes, all within the multi-value context of society. The necessary decision framework needed must ensure that: reasonable decisions can be made, and must identify and include all the responsible parties for making and enacting these decisions. Output from the decision framework must be cast in the terms of discrete actions, such as instructing groundfish managers to integrate salmon by-catch into their models, or estimating population impact after an ecosystem specific management action, as well as direction for the technical support community on the level of precision or uncertainty that is acceptable for managers to make informed decisions.

Marine (ocean/estuary) salmon population ecology

Ocean survival of Columbia River salmon is naturally low and highly variable (Haeseker et al., 2012), with current estimated average ocean smolt to adult survival (Bonneville Dam to Bonneville Dam) for Chinook salmon around 1%, although historical survival was likely higher. The importance of ocean conditions to the survival of Columbia River Basin salmonids is demonstrated by the strong relationships between ocean conditions and adult returns and overall smolt to adult return rates (Burke et al., 2013, Miller et al., 2014, Peterson et al., 2014). A combination of physical processes and both top-down and bottom-up biological processes affect the early ocean survival of juvenile salmon, but the nature and strength of these relationships varies among species, ESUs, stock groups, and life history types. That no single environmental factor accounts for variability in ocean survival across species and stock groups is not surprising given differences in such factors as ocean distribution (Van Doornik et al., 2007, Teel et al., 2015, Van Doornik et al., 2019), diet (Daly et al., 2009), migration corridor experience (McCann et al. 2023) and time and size of ocean entry (Weitkamp et al., 2015). In particular, data consistently point to the idea that the first months that juvenile salmon are in the ocean are critical to their overall ocean survival and that subsequent adult returns for many stock groups are determined during these first few months at sea. To further complicate matters, the factors that have the greatest impact on marine survival likely vary among years.

Predators are thought to be particularly important drivers of marine survival, for both juvenile and adult salmonids. For example, pinniped presence overlaps with the height of ESA-listed adult salmon returning to the Columbia River and a significant portion of the juvenile salmon out-migration. To date, the majority of the effort to both study and address pinniped predation has focused on a predation hot spot, within 0.25 mile of Bonneville Dam where annual estimates of adult salmon consumption range from less than 1% to over 3% of the total adult return. Pinnipeds within this area are primarily California sea lions and Stellar sea lions, making up less than 10% of the total Columbia River sea lion population. Across a broader area (i.e., from the estuary to Bonneville Dam), estimates of adult salmon consumption by pinnipeds during the spring ranged from ~50,000 to ~225,000 fish (20-44% of the return) annually between 2010 and 2015 (Wargo Rub et al. 2019). Data also indicates there is higher predation on early returning ESUs compared to late spring/early summer migrants (Sorel et al. 2020). It is important to note that the current focus on this area does not imply it is the only area of concern - the mouth of the

Columbia River and the coastal environment along Oregon and Washington is home to large numbers of harbor seals, California sea lions, Stellar sea lions, and harbor porpoises. Birds and fish are also known to be top predators on salmonids.

Climate change impacts on marine ecosystem

Climate change is altering marine environments used by Columbia River basin salmon and steelhead; increased frequency and magnitude of marine heatwaves, changes to the intensity and timing of coastal upwelling, increased frequency of hypoxia (low oxygen) events, and increasing ocean acidification. These factors reduce and will continue reducing ocean productivity for salmon and steelhead. While there can be periods of good ocean conditions for salmon and steelhead (near-shore conditions off the Oregon and Washington coasts were considered good in 2021), the magnitude, frequency, and duration of downturns in marine conditions are expected to increase over time due to climate change. Historically, sea surface temperatures over large areas of the North Pacific have been very strong correlates of salmon marine survival coast-wide (e.g., Chasco et al. 2021; Johnstone and Mantua 2014; Mantua 2009; Mueter et al. 2005). Consequently, when we extrapolate this correlation into the future using climate change projections from earth systems models, we predict catastrophic declines in future marine survival, particularly for interior Columbia Basin spring/summer Chinook salmon (Crozier et al. 2021), also most other salmon species (Abdul- Aziz et al. 2011). However, numerous analyses have shown that the relationships between climate indices and salmon survival change over time (Gosselin et al. 2021; Litzow et al. 2019; Wainwright 2021). Therefore, the results of climate change for salmon marine survival might not be that easy to predict.

On the physical side, the climate indices most often used, the Pacific decadal oscillation and the North Pacific Gyre Oscillation, are complex phenomena that change their relationships to each other over time. The PDO, for example, is not a simple response to global atmospheric temperatures. From a salmon perspective, it is the ecosystem response to environmental conditions, not thermal stress alone, that is most critical. We know this because even relatively warm ocean temperatures, such as during the marine heatwave of 2014-2016, are generally within the optimal range for juvenile and adult salmon. We suspect that the climate change threat for salmon is mediated by interactions with prey and predators. Climate impacts on oceanographic processes and primary productivity are complex, but they have been and continue to be the focus of intensive study. Less-well studied are the likely impacts of climate change on secondary and higher trophic levels, including top predators of salmon. Understanding these complex interactions currently, and how they may evolve in response to climatically and ecologically novel ocean conditions (Brodie et al. 2022; Muhling et al. 2020; Smith et al. 2022) is necessary to predict salmon responses to climate change, and is critical for identifying anthropogenic actions that minimize salmon declines in response to these pressures.

Climate-driven changes in ocean temperature and other physical attributes will result in abundance and distributional changes for many important marine species. Southern predators, such as many marine mammal species, fish such as hake and tuna, and even birds may locally increase in abundance near the Columbia River. Recent evaluations of the impact of sablefish show that they can be strong competitors of juvenile salmon, reducing salmon consumption and stomach fullness (Daly et al. 2024). Forage fish are also an important group that can have wide-ranging interactions with salmonids, as salmon prey, competitors, and alternative prey to salmon predators.

Linkages between freshwater and marine life stages: carryover effects

In completing their lifecycle, salmon and steelhead migrate between fundamentally different and distinct ecosystems. Legacy or residual impacts of experiences can persist across these transitions, and as such, link marine and freshwater environments at the level of individual fish. These “carryover effects” include latent mortality, delayed mortality, and more generally cross-life-stage effects that are sublethal in the current habitat or life stage and that affect (positively or negatively) future salmon responses such as survival, age at maturity, and adult size.

As salmon and steelhead spawn, rear, and migrate downstream in the freshwater environment, they can experience a range of sublethal conditions (low primary productivity, habitat degradation, low stream flows, high water temperatures, competition, and stress and delay associated with juvenile downstream migration through the hydrosystem) that can have carryover effects on marine survival and their age and size at maturation. Salmonid survival is comparatively low in the ocean and, with the exception of harvest management strategies, the conditions of the marine environment are, at least in the near term, essentially out of direct human control. Thus, freshwater-to-marine carryover effects are important to consider for mitigating any negative impacts from the hydroelectric power system, hatcheries, poor freshwater habitat conditions, and a warming ocean. A few freshwater environmental and biological indicators are identified to have relatively consistently affected marine survival and age and size at maturation; these indicators include: river flow and temperature, juvenile fish length, growth indices, seasonal migration timing, water transit time, hydrosystem passage route (McCann et al. 2023), and genotype by environment interactions (Larsen et al. 2006, Petrosky and Schaller 2010, Haeseker et al. 2012, Gosselin et al. 2018, Harstad et al. 2018, Larsen et al. 2019, Gosselin et al. 2021, Larsen et al. 2022, Bond et al. 2024, Gosselin et al. 2024, McCann et al. 2024). Thus, there is significant potential for management to help improve marine survival and increase the proportion of larger older adults with considerations of freshwater-marine carryover effects.

Recent and ongoing research into carryover effects from freshwater to survival in the estuary and marine environments has focused primarily on two groups of factors: autecology of the fish (e.g., size, life history expression) and the suite of environmental conditions experienced in the freshwater (e.g., temperature, flow, hydrosystem operations). For example, Snake River Chinook survival is elevated amongst those fish with fastest travel times and fewest powerhouses encountered (Haeseker et al. 2012; McCann et al. 2024), earliest emigration timing (Gosselin et al. 2018, Chasco et al. 2021, Bond et al. 2024), and among the largest smolts (Gosselin et al. 2021, Gosselin et al. 2024, Bond et al. 2024); however, there is considerable variation among migration years that remains unexplained. That is, there are years when early migrating fish have poor survival indicating an interaction of timing with favorable conditions (Chasco et al. 2021). Similarly, larger smolts emigrating from freshwater tend to have a higher survival compared to smaller smolts, but there are years when the effect of fish length is weak or non-existent (Bond et al. 2024). In addition to size, growth rate in the fall and spring prior to smolting is also positively correlated with smolt-to-adult return survival (Beckman et al. 1999, Norrie et al. 2022, Gosselin et al. 2024), indicating benefits of freshwater physiology to marine survival. Among freshwater environmental factors, Snake River Chinook smolt to adult return is elevated when mainstem rivers are cooler, flow is higher, and the seasonal snow-water- equivalent index (SWE) is elevated (Gosselin et al. 2021). Although the mechanism is unknown, cooler temperatures may be less stressful and have lower metabolic costs during the migration period. Elevated flows and SWE may be linked to more rapid emigration from the system and fewer interactions with powerhouses than during periods of lower flow (Faulkner et al. 2019, Gosselin et al. 2021).

Decision support tools for ecosystem based management and climate change

In a changing climate, the ocean distribution, survival, growth, and other biological attributes of Columbia River salmon and steelhead are expected to differ from historical patterns. These changes, in turn, will likely interact with ocean management measures. For example, changes in ocean distribution may shift which ocean fisheries encounter which salmon stocks, while changes in growth rates may shift the ages at which individuals mature and return to spawn. While such changes in biological parameters may be evident in retrospect, developing environmental or ecosystem based indices that can anticipate or predict changes to biological parameters are key to responding to a rapidly changing climate. Since 2012, the California Current Integrated Ecosystem Assessment (CCIEA) has compiled and synthesized physical, ecological, economic and social data sets into ecosystem status reports, to provide contextual information on ecosystem status, trends, and dynamics for managers and the public (e.g., Leising et al. 2024). This compilation includes many ecological indicators related to early marine survival of Columbia Basin Chinook and coho salmon, based on the well-established “stoplight tables” developed over the past several decades by the NWFSC. Additional stoplight tables created for Central Valley and Klamath River fall Chinook have placed further emphasis on habitat indicators from the freshwater and estuarine phases. Recognizing that relationships between indicators and salmon can be dynamic, we have begun exploring evidence of nonstationarity of climate-salmon relationships on the West Coast (Litzow et al. 2020). We have also examined threshold relationships between climate drivers and salmon forecast model performance (Satterthwaite et al. 2020), and between salmon production and a range of environmental drivers that could trigger management responses (Munsch et al. 2020).

In addition to tracking physical, ecological, economic and social indices’ dynamics and trends for ecosystem management, results from decision support tools such as salmonid lifecycle models can be used to estimate potential responses to management actions (Section 4.0). These models of salmon populations use functional relationships that integrate effects of stressors at multiple life stages, spatial locations, current and future environmental conditions. Salmonid lifecycle models can be used to assess cumulative effects of combinations of management actions.

3.0 Current Research and Monitoring

One of the big unknowns is how well future ocean ecosystems will support salmon, in part because changes in open, speciose ecosystems are extremely difficult to predict. Recent unexpected proliferation followed by retreat of major consumers, such as Humboldt squid (*Dosidicus gigas*) (Litz et al. 2011) and *Pyrosoma atlanticum* (O'Loughlin et al. 2020), emphasize the unpredictability of nature, and especially responses to climate change. That said, ecosystem changes observed during recent strong El Niños and marine heat wave events provide one representation of conditions that could be considered normal in the future. These events have resulted in changes in the distribution and abundance of a broad range of taxa across all guilds, including copepods, ichthyoplankton, squid and other invertebrates, fishes, sea birds, and marine mammals (e.g., Leising et al. 2015, Sakuma et al. 2016, Auth et al. 2017, Peterson et al. 2017, Morgan et al. 2019, Chasco et al. 2022). These changes altered the abundances of juvenile salmon prey, competitors and predators, which depressed marine survival for many salmon populations, especially during the extreme year of 2015. However, some coastal and Columbia River salmon populations have been resilient through these potentially deleterious ecosystem changes, such as Columbia River fall Chinook that returned in 2022 and Columbia River sockeye salmon in 2024. It is unclear whether these populations will continue to thrive as the ocean changes further, or whether adaptation or slower changes in other populations will shift the balance among winners and losers. What is clear is that the more we know about ocean ecosystem processes, the more we can accurately anticipate salmon responses.

NOAA's NWFSC has a long history of estuarine and marine research and monitoring. For example, NWFSC led pioneering work to examine stock-specific survival and migration timing of juvenile salmon within the Columbia River estuary starting in the 1970s (Dawley et al. 1986), the high frequency sampling on the Newport Hydrographic Line has been operating continually since 1996 and the Juvenile Salmon Ocean and Ecosystem Survey began in 1998. In addition, there have been numerous smaller scale or temporally bound research efforts that contributed to our collective knowledge on estuary and ocean salmon ecology. Below are some of the current efforts led by the NWFSC.

Ongoing, long-term research and monitoring

Juvenile Salmon and Ocean Ecosystem Survey

The Juvenile Salmon and Ocean Ecosystem Survey (JSOES) project was initiated in 1998, funded by Bonneville Power Administration, to address the role of the ocean in determining early marine growth and survival of Columbia River basin salmonid stocks. Survey efforts are designed to study juvenile salmon as they enter the ocean and during their first few months of marine residence, as well as to monitor the ocean conditions experienced by these fish. Integral to addressing these issues, the JSOES project has identified when and where specific ESUs and stock groups of juvenile salmon are found in the plume and nearshore coastal habitats. During the surveys, researchers collect physical data with CTDs, lower trophic level data with bongo and vertical nets, and nektonic organisms of a range of sizes with a large surface trawl. Starting in

2003, researchers also performed an annual visual survey to quantify the distribution and abundance of seabirds. There are also occasional process-based studies to address specific hypotheses, such as the role of the Columbia River Plume front on aggregating salmon and other organisms. Currently, the JSOES project involves two surveys per year (one in May and one in June) off the coast of Oregon and Washington, each lasting between 7 and 11 days. Historically, there was also a September survey, which provided important ecological information for fall-run Chinook and coho salmon.

Although focused on salmon, this project explicitly recognizes the complex ecological processes that impact salmon survival in the ocean. Both biological and physical metrics that are related to salmon survival continue to be monitored to better understand these causal mechanisms. For example, common murres (*Uria aalge*) and sooty shearwaters (*Ardenna grisea*) are the most abundant fish-eating birds present in marine areas occupied by juvenile Columbia River salmon (Zamon et al. 2025, Phillips et al. 2017, Zamon et al. 2014), accounting for 80% of seabirds near the Columbia River mouth during late spring and summer. Importantly, having abundant marine forage fishes to serve as alternative prey for these avian predators potentially reduces predation impacts on juvenile salmon by up to 70% (Phillips et al. 2021). These and other results from the JSOES project can help inform existing management decisions as well as identify new levers that could be used to improve salmon ocean survival.

Newport Hydrographic line

High frequency sampling on the Newport Hydrographic (NH) Line program was initiated in 1996 and provides the information needed for understanding the connectivity between changes in ocean-climate and ecosystem structure and function. The 25+ year time series provides high frequency data that characterizes the pelagic habitat and prey resources that support commercially important and ESA protected species. Sampling along the NH Line has been conducted twice monthly to monthly, year round, since 1996. Sampling occurs at 7 stations evenly spaced from 1-25 nm from shore. At each station, water column properties (temperature, salinity, Oxygen, aragonite) are measured; surface water is collected for nutrients, chlorophyll, and phytoplankton; and zooplankton and fish and invertebrate larvae are collected with plankton nets. Data from these high-frequency efforts are distilled into ocean ecosystem indicators that characterize the habitat and survival of juvenile salmonids and data are available on a near real-time basis to managers, researchers, and the public. The longevity of the NH Line time series creates a powerful baseline for understanding seasonal and interannual variability, thereby providing the assessment of ecosystem impacts from an unpredictable future.

Survival through the Estuary

Since 1995, NWFSC staff detect juvenile salmonids tagged with passive integrated transponder (PIT) tags in the Columbia River estuary using a surface pair-trawl fitted with a PIT-tag detection antenna towed at Rkm 75 (Ledgerwood et al. 2004, Holcombe et al. 2019). Pile-dike arrays have been added in recent years and have increased detections through the estuary The program is used to evaluate survival and migration timing of tagged salmon migrating through the hydrosystem, including potential differences between transported and run of the river fish. It provides a long-term record of annual estimates of migrating timing, migration rates, and survival, which can be compared to factors such as river flow and temperature, upstream conditions, and fish condition.

SRKW Monitoring

The NWFSC and collaborators have conducted long-term population and population process determinant monitoring on Southern Resident Killer Whales. The demographic, diet, and behavioral data generated by this program forms a key baseline of nearshore ocean ecosystem health and function.

Recently initiated, short term, high intensity research

Ocean predation

The Columbia River mouth acts as a funnel, through which all anadromous salmonids migrate, as juveniles and again as adults. This funnel can also attract large numbers of predators, such as mammals (Brown et al. 2020), birds (Zamon et al. 2025, Phillips et al. 2017, Phillips et al. 2021), and competitive and predatory fishes (Emmett and Krutzikowsky 2008; Daly et al. 2024). Although avian predation is well-estimated in the Columbia River and Estuary each year (e.g., Caspian terns and double-crested cormorants; Evans et al. 2024), estimates of predation rates by the more marine oriented avian predators, such as common murres and sooty shearwaters, are lacking due to funding constraints. Similarly, for the large number of pinnipeds in the Columbia River plume and nearshore environments, predation research is limited to one project led by researchers at Oregon State University (OSU). For other marine predators, such as piscivorous fishes, direct estimates of predation on salmon is virtually nonexistent. As part of an Inflation Reduction Act (IRA) funded project, researchers at the NWFSC and OSU are evaluating the capability of thermal imaging cameras to quantify the abundance and distribution of warm-blooded predator species, including both avian predators and marine mammals. As part of this 3-year effort, researchers will develop an AI-based algorithm to automatically identify species in captured video, vastly improving our ability to 1) survey large areas of the marine environment and 2) create a continuous estimate of predator abundance at a single location, such as the Columbia River mouth. Once developed, this methodology can help quantify the mechanistic relationship between marine predator abundance or distribution and salmonid marine survival.

Lower trophic level indicator development

As part of an IRA-funded project, the NWFSC is developing new indicators of primary production and lower trophic level energetics for improved fisheries management and ecosystem assessment using advanced technologies. Part of this effort will be to routinely monitor phytoplankton community composition using a robotic microscope (the Imaging Flow Cytobot [IFCB]) and high throughput sequencing, and link these data to measures of the nutritional value of lower trophic levels that support juvenile salmon using lipid and fatty acid analyses. Expanding these indicators to cross-Center, coastwide fisheries and ecosystem surveys will provide insight into the structure and function of marine food webs beyond commonly used measures of chlorophyll-a that have limited value as indicators of the quality of food available to zooplankton and higher trophic levels, tracking shifts in primary productivity and water masses, and also providing an early warning for Harmful Algal Blooms (HABs). These data will also be used to evaluate changes in ocean biodiversity, detect changes related to offshore wind energy development, and to parameterize models for Climate, Ecosystems, and Fisheries Initiative (CEFI) scenarios on changing ocean productivity.

Valuation of near-shore, estuary, and freshwater habitat

Determining the value of habitat for protected and managed species is a significant management challenge for a number of reasons, including the difficulty of collecting data at meaningful spatial and temporal scales for the species of interest and accurately reflecting the ecological value of the habitat in question. For example, descriptions of habitat value "as the fish see it" can be elusive because anadromous fish (or other protected species such as green sea turtles) experience the benefits of a habitat mosaic, which reflect ecosystem functions across multiple, sequential, and dynamic habitats.

Given these challenges, how do we value coastal marine, estuarine and freshwater habitats? NOAA Fisheries NWFSC is engaged in a new initiative that presents a unique opportunity to enhance partnerships and strengthen the science and collaborative decision-making tools. This novel effort will support management of near-shore marine, estuarine and freshwater habitats and the species that use them. To achieve our overarching goal to identify, evaluate and strengthen existing habitat valuation approaches, we will identify and summarize advantages and disadvantages of habitat valuation approaches (tools, models, calculators) used by NOAA Fisheries West Coast Region and others. Through this exercise we will identify opportunities for improving current tools and perhaps suggest other approaches. The evaluation of existing tools will explore user accessibility and stakeholder input, but ultimately focus on the conservation effectiveness of each tool.

Fresh water conditions/experience

Given the high level of uncertainty regarding future ocean conditions and the salmon response, as well as the potential for management actions to influence this life stage, we are adopting a multi-model approach to inform the interior spring Chinook salmon and steelhead life cycle models. Our goal is to build a set of models with the minimum complexity that is needed to capture 1) individualistic responses to climate change in multiple species that interact strongly with salmon and 2) a range of management actions by which NOAA and other managers could influence the marine life stage. Future work can extend this learning to ocean type life history pathways, and our ecosystem approach in general lends itself to evaluating broader productivity changes involving other species of interest.

We began with more strategic modeling approaches to justify the level of complexity and a reduced set of indicators to be included in the final marine module for the life cycle model. Strategic approaches involved three explorations of alternative mechanistic hypotheses regarding community organization. We took this step because of the importance of model design in interpreting the results, given our level of uncertainty in how to represent current and future marine ecosystems. We first conducted a qualitative network analysis with a wide variety of assumptions about positive and negative species interactions to specify the minimum level of complexity. Second, we used an end-to-end ecosystem model approach to quantify biomasses of relevant species groups prior to and during the recent marine heatwave and fully account for indirect effects of species groups that would be left out of the final model. Third, we used a structural equation model framework to organize possible indicators of interannual variation in the selected functional groups (including salmon) nested within expected trophic relationships throughout the marine period across the North Pacific.

The final (tactical) marine stage model to be applied in the Chinook salmon life cycle model scenarios will be an integrated model that accounts for individual fish experiences for carryover effects from freshwater and ocean growth conditions through the age at return. We expect this model to explicitly account for freshwater effects on fish condition that can include length, smolt timing, exposure to sublethal effects of water quality, and an initial predisposition to return at a certain age. Estuary temperatures and flows will affect mammalian and avian predation and salmon movement rates into and through the Columbia River Plume. Oceanographic conditions derived from regional ocean models will be used to drive co-occurrence indices for growth and predator exposure in the estuary, Northern California Current, and North Pacific. Ecological conditions in the North Pacific will be tested to see if they improve model fits of adult return at age over general climate indices. If so, they will be assessed under climate change conditions. Finally, pinniped and killer whale encounter risk in climate, predator management, and fishery scenarios will determine adult survival during their final return to Bonneville Dam. The model will be able to explore management scenarios that influence habitat and hence salmon condition and marine species from tributary, mainstem, estuary, and nearshore actions. Fisheries and hatchery production that influence the abundance of spring and fall Chinook and steelhead, as well as pink and chum salmon will be tested for importance, as will other major fishery targets such as hake and other groundfish. Significant Chinook salmon bycatch has been reported in these fisheries, but they also could reduce the abundance of piscivorous predators. This intermediate complexity model will be supported by simpler models with a simpler ecological structure, such as those applied in Chasco et al. (2021) and Bond et al. (2024).

The steelhead marine stage model will focus most directly on avian predation in the estuary fit to data from PIT tags retrieved from nesting colonies. We will explore all of the covariates developed for the Chinook salmon model in the steelhead model, although the latter will likely not include a variable propensity to return at a given age.

4.0 Gaps in Knowledge and Research

Full life cycle sensitivities

While collectively we have established a significant body of knowledge about impacts to salmonids at different life stages, there is considerable uncertainty due to a lack of knowledge about particular life stages. Also, we observe year to year variability in the freshwater and marine environments that has dramatic impacts on population abundances through time. One way to balance uncertainties, knowledge gaps, and model complexity with observed process (biological and physical) variability is to conduct sensitivity analyses.

Sensitivity analyses are often conducted with decision support tools, such as LCMs, to understand which parameters representing life stage transitions or biological characteristics of a population are having the most influence on the decision support results. One at a time parameter manipulations, or local analyses are typically done on simpler models, and global, or simultaneous parameter manipulations are used for more complex models, or multi-model systems, with interacting effects. As such, sensitivity analyses can be used to identify gaps in our knowledge and weaknesses in our predictive capacity, as well as to identify priorities for increasing the depth of our knowledge, as they indicate where uncertainty is most likely to propagate forward when making population projections.

Ocean ecosystem

Stock specific stoplight

NOAA and OSU researchers have built and annually update a stoplight chart approach to summarizing a large suite of indicators of ocean conditions. This chart, and the data in it, have been used for many years by researchers, managers, and the public to better understand current conditions and expectations for marine survival of a given cohort of salmon. However, given the clear differences in how ocean conditions impact various stocks of salmon, using a single stoplight chart for all stocks is inadequate for many needs. Many existing and future uses of a stock-specific stoplight chart, such as forecasting adult returns, refining a management action, and estimating potential climate impacts, require a mechanistic underpinning of the individual indicators for each stock. This level of precision in pairing an environmental variable with a specific stock's response necessitates a greater scientific effort than is currently supported, but clearly highlights the role of integrated science and management frameworks in order to most effectively evaluate EBFM options.

Top-down

Predators

Mean and variance of predation rates on salmonids in the coastal and offshore marine environments probably represent the largest knowledge gap in all of salmon science. A few estimates exist for a particular predator species consuming a particular stock group during specific years (Chasco et al. 2017); for example, we lack any information on salmonids in the diets of small toothed whales. Yet a general understanding of which predator species are having the largest impact on salmon marine survival is lacking. For Columbia River stocks, very little information exists on how potential salmonid predators respond to environmental conditions, variability in salmon abundance (spatially or temporally), and availability of alternative prey (such as forage fish) as a potential mitigation factor for predation rates on salmon. There is currently no empirical information about pinniped predation on late summer/fall run adult salmon and steelhead below Bonneville Dam, and, importantly, no contemporary information about predation on any juvenile outmigrants, although both are likely to be significant. For example, in the mid-1990s, Laake et al. (2002) identified significant predation by harbor seals on juvenile Chinook salmon in the spring and adult Chinook salmon in the fall.

Additionally, from 2002- 2021, juvenile salmon have been identified in 13% of scat collected from California sea lions and Steller sea lions hauled out at the East Mooring Basin, Astoria, Oregon (ODFW, S. Riemer pers. comm.). Although the JSOES project monitors avian predator abundance and distribution, there is very little empirical information about how important salmon are to their overall diet, how that might fluctuate through the salmon migration season, and how factors that drive the spatial and temporal patterns in forage fish distributions might change the relative magnitude of salmon in these predators' diet.

In addition to lacking basic information about Columbia River pinniped and avian predation on salmonids by predator species, we lack information about how the ecosystem influences Columbia River predator abundance and diet from year to year. There are a number of specialist predators such as SRKW that may focus on salmon and whose population-level bioenergetic demand is increasing with their abundance following recovery efforts. However, it is naive to ignore the diverse and rich taxa that feed more opportunistically on salmon, under specific environmental and forage conditions. For example, predators such as Pacific hake and common murre may show little proclivity for salmon specifically (i.e., little observable proportion of their total diets), but during periods of habitat compression and reduced alternate forage they each have a demonstrable impact on salmon recruitment (Wells et al. 2017, Wells et al. 2023). Also, a combination of poor ocean conditions off the coast of California and robust eulachon returns to the Columbia River may have served to draw large numbers of sea lions into the river during 2013 – 2016. Emmett and Krutzikowsky (2008) found that Pacific hake and jack mackerel near the mouth of the Columbia River mainly consume krill and forage fish, but also juvenile salmon (largely subyearling Chinook). Accounting for the population sizes of the predators and feeding rates, they estimated that between 0.7 - 6.4 million salmon were consumed each month by hake and 0.1 - 0.4 million by jack mackerel during the months of May, June, and July. Extension of their results with an additional 5000 salmon gut samples (thus doubling their dataset) reconfirmed these assertions to 2019 (Wells et al. 2023). Unlike many mammal and avian predators that are easily observed by ongoing research efforts, many piscivorous predators have largely not been evaluated (e.g., Pacific dogfish, salmon sharks).

Changes in predator abundance and distributions

While salmon entering the ocean and coastal waters are relegated to begin their ocean residence near their natal sources, the predators that feed on them are not. Predator complexes can change their distribution to accommodate variability in the ecosystem shifting inshore where, under certain circumstances, there may be improved foraging opportunity. Pacific hake, for example, move north into the Northern California Current during warmer conditions and often move inshore when their dominant prey taxa, krill, are less available. Presumably, Pacific hake move in to feed on lipid-rich forage fishes, including anchovy, herring, and smelt (Daly et al. 2010). These prey items are the staple to salmon diets as well (Wells et al. 2023). Juvenile salmon are likely to converge with foraging Pacific hake on a shared resource on the shelf break and, hence, dramatically increasing population impacts of predation by Pacific hake on salmon (Emmett and Krutzikowsky 2008). This dynamic is not unique to Pacific hake and salmon. This may be a general predator behavioral response to ecosystem variability. Inshore shifts have been noted for common murre (Wells et al. 2017) and Humpback whales (Santora et al. 2020) in the Pacific coastal waters and silver hake, red hake (Friedland et al. 2012) and atlantic cod (Hedger et al. 2011) in Atlantic coastal waters during periods of reduced prey availability. Moreover, interannual variability in predator abundance can dramatically change the spatial overlap between predators and salmon, as recently shown with sablefish (Daly et al. 2024).

Fronts, eddies, and similar oceanographic features can also act to concentrate salmon with their predators (Siwicke et al. 2019). These areas are used by salmon (Sabal et al. 2020), but also predators seeking similar prey, and salmon as well (Arostegui et al. 2022). The assumption is that where and when there are features consolidating prey for apex predators, there is greater likelihood of overlap and hence predation on salmon.

The changes in abundance and distribution can result from interannual variability in physical drivers, but can also stem from larger-scale changes such as climate warming and shifts in large-scale transport patterns. We have some indications of climate-driven range shifts for many species, but lack a comprehensive estimate of the resulting community structure salmon may be experiencing in the coming years and decades.

Size dependent predation

Size-selectivity for juvenile salmon in the marine environment is often assumed but not always supported by evidence. It was not significant for Chinook salmon in the Puget Sound (Gamble et al 2018) and only modestly observed by Claiborne et al. (2011) in coastal waters of Washington, with no evidence that it affected recruitment. However, under extreme, or highly unproductive conditions, Chinook salmon cohorts can fail due to significant size-selective predation (Woodson et al. 2013). Bond et al. (2024) quantified the high interannual variation in size effects while modeling carry-over effects from freshwater on Snake River spring/summer Chinook salmon marine survival. We attribute the rarity of observable size-selection in juveniles to the specific conditions that are necessary to cause it, including habitat compression, limited alternate forage, and poor growth conditions for salmon entering the ocean. In fact, Henderson et al. (2019) and Fiechter et al (2015), each using numerical simulations, demonstrate that growth in early marine residence is tied significantly to recruitment. Vasbinder et al. (2023) further corroborated these results through analysis of cohort-specific growth patterns demonstrating that the date at which a salmon grows out of the gapes of Common murre was likely as early as mid-June in productive years for salmon and was delayed by two months in years such as 2005. Importantly, there is also evidence that some specialist predators, such as killer whales, may feed preferentially on larger salmon, which can complicate our ability to identify evidence for size selectivity.

Bottom-up

Changes in prey availability

During early marine residence, a period of high mortality, growth and survival of juvenile salmon is correlated with various metrics of ocean conditions, including prey quality and abundance. Diets of juvenile coho and Chinook salmon and steelhead during their first summer in the ocean show that they primarily consume juvenile groundfish and forage fish, krill, and late stage crab larvae, which in turn feed on small zooplankton such as copepods and early stages of various crustacean larvae. The fish and crabs that salmon consume are spawned in winter and feed and grow to become important salmon prey by spring and summer. The types of prey fish taxa on the shelf in winter are dependent on winter ocean conditions, and are particularly impacted by increasingly frequent marine heat waves. Little is understood about the correlation between ocean conditions and the resulting salmon prey community, other than the high level of interannual variability. Adult krill and late stages of crab larvae have also been shown to change dramatically with ocean conditions, and little is known about the specific mechanisms impacting the biomass of these salmon prey on the shelf from year to year. Increasing our knowledge during this time period could help us understand how key prey of salmon are impacted by physical drivers and how this might change in the future. Ultimately, this understanding could result in well-informed management options to optimize these important taxa for the food web, including salmon.

Competition from large scale hatchery releases

Fish hatcheries have been used extensively for over a century to produce fish for harvest, and in recent decades to supplement wild populations (for harvest and spawner numbers), to sustain wild populations, and to mitigate for large-scale environmental impacts such as hydropower project implementation and operation. While hatchery fish support most West Coast salmon fisheries, there is considerable concern about hatchery impacts to wild populations. For example, in a review by McMillan et al. 2023, most (70%) studies evaluating hatchery impacts to wild salmon or trout populations globally found adverse effects, primarily through genetic or ecological means. This is a particular concern in the Columbia River because in an attempt to mitigate for productivity lost to the federal Columbia River hydrosystem, most (>70%) outmigrating steelhead, yearling Chinook, and coho are of hatchery origin (Weitkamp et al. 2012, 2022). In fact, hatchery production has been the primary mitigative tool employed by the region for that lost productivity. And while there is an increased proportion of hatchery fish in the ocean, the overall number of Columbia River salmon in the ocean is still less than would have been supported historically in that ecosystem.

Nonetheless, we know from extensive research and implementation across facilities in the Columbia River that hatchery practices can be modified to: i) alter development, survival and maturation profiles (Beckman et al. 2017, Harstad et al. 2023); ii) modify rearing and release locations to influence spawning location of returning adults (Dittman et al. 2015); and iii) alter growth rates and release practices to reduce residualism, speed migration, reduce the potential for negative ecological interactions (Tatara et al. 2019), and possibly mitigate for size-selective mortality (Berejikian et al. 2017) that may contribute to domestication selection and fitness loss (Araki et al. 2008). Necessary refinements may be hatchery-specific and tailored to the receiving environment or more generalized. Laboratory-scale experiments backed up by hatchery-scale studies provide the most robust basis for making adjustments to hatchery programs within the legal constraints on release numbers. Hatchery-scale studies designed to better estimate survival of hatchery salmon during their ocean residency, instead of relying on smolt-to-adult return metrics, might provide further information regarding competition and environmental conditions in the ocean.

In the Pacific Ocean, the weight of evidence suggests that the abundance of pink salmon (heavily augmented by hatcheries around the Pacific rim) can affect the growth and recruitment of other species (sockeye in particular), but within the Columbia Basin has thus far only been linked to growth of Snake River steelhead (Vosbigian et al. 2024), which have a far more offshore migration pattern and therefore likely overlap pink salmon more than other Columbia salmon (Beamish 2018). Competition from Columbia Basin hatchery production has not been shown to affect ocean productivity of Columbia River Basin stocks. Furthermore, the numbers of salmon released from Columbia River Basin hatcheries are largely legally mandated (e.g., US v Oregon). Therefore, research to improve the performance of hatcheries should focus on mechanisms that show the greatest promise to benefit supplemented or augmented populations and minimize effects on co-mingling natural populations.

Growth dependent survival

A time series of juvenile salmon growth has been developed as part of the JSOES survey (2000-present) by measurement of the hormone IGF1 that is an index of body growth rate. Interannual variation in growth during this period is well correlated with an index of juvenile salmon prey collected in bongo nets during the JSOES survey. During the first decade of the survey (2000 - 2009) there was a correlation between growth indices and subsequent adult survival of either interior Columbia River spring Chinook salmon (Bonneville to Bonneville PIT- tag data) or Columbia River coho salmon (cwt-based OPIH SAR). This relationship suggests bottom-up regulation of the marine survival of Columbia River salmon may have occurred.

Subsequently, there has been a distinct increase in IGF1 values (2010, 2011) and there is no apparent correlation between juvenile salmon growth and survival in this later period (2010 - 2022). The lack of relationship between juvenile salmon growth and adult return in this second decade of the survey suggests an ecosystem shift has occurred and that a different mechanism is regulating early marine survival of salmon during this period. Certainly, the presence of extensive marine heat waves during this period (2010-2022) supports the inference that ecosystem shifts may have occurred. This finding of decadal level change in ecosystem relationships in the California Current echoes similar findings of non-stationarity in ecosystems in the North Pacific (Litzow et al. 2018, 2019). These findings highlight the need for continued monitoring in the California Current to understand if, how and when foundational ecosystem relationships are altered, impacts of these changes to salmon survival, and how that affects our ability to forecast salmon abundance.

Salmon EBFM

Ecosystem based fisheries management (EBFM) is increasingly providing a framework for accounting for indirect effects mediated through the food web that cannot be practically measured by intermediate complexity models. This approach typically accounts for dozens to hundreds of functional groups and uses nearly all available survey and diet data. These models are frequently used in multi-model approaches for strategic fisheries management (Harvey et al. 2020; Kaplan et al. 2018; Marshall et al. 2017; Morzaria-Luna et al. 2022; Tommasi et al. 2021).

Endangered species typically have sufficiently low biomass that they are minor players in these fisheries models, so the main models for the California Current have not been parameterized with ESA-listed salmon in mind. However, bycatch of endangered species can be limiting for fisheries and large biomasses of major stocks likely have important impacts on salmon. To aid both perspectives, we have refined an existing end-to-end ecosystem model to parse out juvenile salmon functional groups from the Columbia River by age and timing (Gomes et al. 2024b), and to explore the impact of the marine heatwave on the Northern California Current (Gomes et al. 2024a). We have used this model also to test the sensitivity of salmon juvenile and adult groups to large scale ocean perturbations, such as a 50% increase or decrease in abundance of all functional groups and across 17 fisheries (Gomes et al in prep). This model could also be used to test the impact of declining salmon populations on fishery targets in climate change scenarios

Estuary ecosystem

Habitat condition

Indirect effects of restoration

Tidal wetlands across the PNW have long been recognized as critical habitat for juvenile salmon, with studies showing benefits primarily to smaller sized life-history stages directly utilizing wetland production in situ (Bottom et al. 2011; Sather et al. 2020). The critical food items are energy rich aquatic and terrestrial insects produced in the wetlands. Larger, yearling life-history types of several species and genetic runs largely avoid shallow tidal channels, yet still consume insect prey derived from within the wetland systems (Weitkamp et al. 2022). Recent studies have quantified the tidal export of this insect prey from wetlands to deeper channels, where larger fish can indirectly benefit from wetland production (Roegner and Johnson 2023). Both natural and restored wetland systems export a varied assemblage of energy-rich prey, which indicates their ecological footprint exceeds their physical space. Wetland restoration can thus have a wider benefit to migrating salmon than previously supposed.

Toxics

Irrespective of source population, all salmon and steelhead stocks in the Columbia River Basin migrate through the urbanized estuary below the Bonneville Dam. The Lower Columbia River Estuary has a long history of industrialization, and the region is experiencing high rates of urban/suburban/exurban growth. Habitat monitoring by NOAA and other researchers has documented widespread exposure to toxic chemical pollution in the estuary, reflecting both historical and modern human land uses. This includes persistent industrial pollutants (metals, PCBs, DDTS, PCBEs, etc.), thousands of chemicals in untreated urban stormwater runoff (particularly 6PPD-q from the transportation grid), and hundreds of pharmaceuticals and other household chemicals from wastewater treatment discharges.

Outmigrating salmon traverse this chemical gauntlet in the estuary, and those that feed below Bonneville are disproportionately exposed to chemicals that accumulate and magnify in estuarine food webs (e.g., PCBs). To date, exposure risks have been widely documented, particularly for juvenile Chinook [multiple NWFSC field studies by Johnson, Arkoosh, and others]. Chemical habitat degradation is most extensive in the greater Portland and Vancouver metropolitan areas, and ongoing patterns of human population growth and development are expanding the impacts of pollution on salmon stocks that reside and feed in the estuary, particularly in proximity to humans. Although certain chemicals cause outright fish kills in the estuary (e.g., the lethality of 6PPD-q to coho and steelhead), the vast majority of contaminant responses are sublethal, delayed-in-time, and extensively influenced by parallel habitat stressors – e.g., increasing thermal stress in response to climate change.

Toxics are therefore an important consideration for carryover effects in the ocean – they cause delayed mortality by reducing growth, increasing pathogen susceptibility, etc. Although population-scale losses attributable to pollution in the estuary represent a major source of management uncertainty at present, these carryover effects have been incorporated into stock specific-population models in the LCR (Lundin et al. 2019). These studies show that habitat restoration focused on clean water and healthy habitats can substantively boost recovery trajectories for ESA-listed stocks. However, more sophisticated modeling work is needed to capture the physiological condition and health of salmon (as predictive of carryover effects), as opposed to simply counting the presence or absence of salmon along their migration corridors to and from the ocean.

Predators

Invasive species

Since the late 1800s, over 35 species of nonnative predatory fish have been intentionally introduced into the Columbia River basin as sport species. Although the rate of introductions of species by federal and state agencies has declined, many nonnative game fish species now inhabit the majority of watersheds in Washington, Oregon, and Idaho. Data on the impacts of predatory non-native fishes on native fishes are scant and outdated, with the size and ecological impacts of game fish populations virtually unknown. This is also true for the impacts of native predators. The studies that do exist are decades old and focus mainly on freshwater mainstem and tributary habitat (see ISAB report 2019, Sanderson et al 2009). Invasive and native predatory fishes are known to inhabit the estuary but the magnitude of impact is unstudied. Filling this knowledge gap on the impact of native and nonnative predators has been identified as an important regional research need.

Bird predation

Predation by birds on juvenile salmon in the Columbia River Estuary is a significant but variable source of juvenile mortality for several listed stocks of salmon and steelhead, removing an estimated 3-20% of juveniles entering the estuary depending on year and fish stock (Evans et al. 2024, Roby et al. 2015, Sebring et al. 2013, Evans et al. 2012). Sites of historic breeding colonies of double-crested cormorants (*Nannopterum auritum*) and Caspian terns (*Hydroprogne caspia*) in the lower estuary are actively managed and monitored for annual, stock-specific predation impacts. Colonies located with access to non-salmonid marine forage fishes in the more saline portions of the estuary have less of an impact on juvenile salmon than those that are near or in tidal freshwater (Lawonn 2023, Good et al. 2022, Collis et al. 2002).

The impacts of avian predators on adult returns remain unclear, despite recent studies. One analysis for steelhead concluded that even though there is significant avian predation on juveniles, predation does not necessarily result in detectable decreases in adult survival. Instead, the relationships among river flow, migration timing, and forage fish availability during the juvenile migration appear to affect adult survival (Haesecker et al. 2020). Other analyses conclude there are meaningful impacts by several avian predators on juveniles and by one avian predator on adult returns (Evans et al. 2023, Payton et al. 2020). Given these conflicting results, the ISAB (2021) concluded it is most prudent for managers to assume avian predation may be a lifecycle risk factor. In any case, estuary avian predator management alone does not appear to be sufficient to recover listed stocks (Lyons et al. 2014), although it could contribute to improved survival as part of broad-based recovery efforts. Current management efforts in the estuary are focused on moving recently-established cormorant colonies from the Astoria-Megler Bridge and upriver of the bridge back to East Sand Island, a location near the ocean where ready access to marine forage fishes like anchovy and smelt is expected to reduce mortality to juvenile salmon (Lawonn 2023).

Given it is still unclear under what circumstances juvenile mortality from avian predation leads to subsequent reductions in adult survival, well-designed, long-term survival experiments comparing adult survival for juveniles exposed to estuary predation vs. juveniles unexposed to estuary predation would be very valuable. Access to readily-available marine forage fishes in lower Columbia Estuary is one key factor known to mitigate avian predation on juvenile salmon and steelhead (Good et al. 2022, Collis et al. 2002). However, there is no current research documenting any aspect of temporal and spatial variation in forage fish abundance in the estuary.

New work to document seasonal changes in marine forage fish availability throughout the estuary and adjacent tidal freshwater zones would contribute directly to high priority management efforts to “pull” avian predators away from locations where non-salmonid prey is unavailable (and predation impacts on salmon and steelhead are therefore high), and “push” them back into locations where access to marine forage fishes reduces predation on salmon and steelhead. Predation impacts of existing brown (*Pelecanus occidentalis*) and growing white (*P.*

erythrorhynchos) pelican populations using the estuary are not well understood. Diet information for those species would fill a knowledge gap. New research is needed to identify cost-effective means to deter birds from nesting or roosting on human-made structures or other locations, especially with respect to the large number of birds using the Astoria-Megler Bridge.

Carryover impacts from salmon freshwater experience

Predictors of later life stage survival

Conditions experienced by juveniles during freshwater rearing and downstream migration influence smolt viability during the first few months in the marine environment and are correlated with increased adult survival (Haesecker et al. 2020; Bond et al. 2024). To date, research has examined fish condition (i.e., larger size) and timing of ocean entry (i.e., earlier) as potential drivers of performance during this critical early marine period. Studies have evaluated the influence of abiotic environmental factors (e.g., stream flow and temperature; Gosselin et al. 2021) and hydrosystem operations (e.g., releases of water over dam spillways and transport of fish around dams and reservoirs) on the condition and timing of fish arriving in saline waters. However, gaps remain in our understanding about what processes get smolts to the marine stage at the right time(s) and in the best condition, and how this varies among years.

Although we understand factors likely to influence fish growth in the freshwater environment, ecological interactions are complex and difficult to predict or manage. For instance, increasing food availability and decreasing predation could maximize growth and thereby allow larger smolts to reach the estuary earlier. However, these actions could also increase competition, producing fewer or smaller smolts. Nor are we certain that producing larger, earlier migrants is even always beneficial. Diverse life history strategies are important for long-term stability of populations that experience a range of extreme conditions. The scientific community is recognizing the need for better assessment of foodscapes (Rossi et al., 2024, Ouellet et al. 2024), which are foundational to predicting growth. And more studies are needed examining predation in freshwater environments, tracking behavior of native and nonnative predators, and diet analysis to see when, where, and how many smolts are being consumed.

Another gap in our understanding is how biological and physical mechanisms interact to optimize the influence of freshwater residency on marine survival, which will only be compounded with climate change. To better understand potential carryover effects from the freshwater environment, we have begun using lifecycle models to follow cohorts (or individuals) from the freshwater environment into the marine environment (and back again over generations). A key challenge is to ensure that outputs from freshwater modules are usable by marine modules. This will be especially important as each system is typically modeled in isolation, each with its own assumptions about stationarity and climate influences. It is unknown what model form and spatiotemporal resolution are needed for fairly evaluating carryover effects. Finally, most research has focused on imperiled populations (such as spring Chinook salmon) where ecological processes may not be functioning well. We could learn much by studying healthier populations (such as some fall Chinook stocks) to examine what makes their strategies so successful.

Toxics

Toxics are ubiquitous in freshwater systems, with sources that reflect myriad human land uses – past, present, and future (emerging). By land area, agrochemical applications of legacy and modern pesticides throughout the Columbia River Basin represent the most widespread conservation concerns for salmon and steelhead. Pesticide loadings to salmon habitats have been extensively documented by federal and state agencies, and commonly contribute to degraded surface water quality in sub-basins with intensive agriculture. Insecticides, herbicide, fungicides and other biological control agents directly affect the health of salmon, or the integrity of freshwater food webs. For example, common insecticides can be highly toxic to juvenile salmon as well as their macroinvertebrate prey, the latter indirectly reducing growth during critical windows of freshwater maturation. Moreover, in multiple ESA biological opinions, NOAA has formally determined that certain pesticides (among hundreds in modern use) are currently jeopardizing the recovery of all ESA-listed salmon populations in the CRB. In addition to agrochemicals, toxics from mining, municipal discharges (wastewater and stormwater), and industrial activities all contribute to poor habitat conditions, with the scale of the impact varying across salmon stocks with different distributions in space and time. Nearly all of the salmon-habitat interactions involving toxics are delayed-in-time. For example, whereas exposures to organophosphate insecticides in the Wenatchee sub-basin may not kill Chinook outright, reduced growth can be expected to increase size-selective predation during seaward migration (fish never make it to the estuary).

5.0 Current and Potential Management Opportunities

Developing management actions in an ecosystem context requires rigorous, formal management scenario evaluation (MSE). While salmon and steelhead from the Columbia River are managed for cultural, conservation, and exploitation purposes across multiple overlapping jurisdictions simultaneously by numerous independent teams, the aggregate result does not constitute an EBFM implementation. The following elements of this section identify management sectors, and the ecosystem components they involve, that offer viable opportunities to improve the effectiveness of Columbia River salmon and steelhead management. In all cases, evaluations of management action efficacy are needed, and are needed in light of existing knowledge and gaps in understanding, current action trajectories, alternative action options, and a changing climate. MSE also requires a clearly defined objective, otherwise, its optimization perspective cannot be realized. As such, a collaborative framework is needed to generate regional objectives that consider the human and natural ecosystem setting of Columbia River salmon and steelhead.

Regionally, the principles of EBFM, and in particular, simultaneous consideration of human and natural ecosystems, have been advanced (NPCC 2014, Murray Inslee 2022, CBP 2022, USFWS 2024). The Northwest Power and Conservation Council, through its program documents, Independent Science Review Panel, and Independent Science Advisory Board, has long supported monitoring of ocean conditions and has endorsed mitigation and management actions that improve survival, growth, and viability of Columbia River fish in varying ocean conditions, while also maintaining indigenous cultures and practices, and vibrant agricultural and industrial economies of the Basin (NPCC 2014 Columbia River Fish and Wildlife Program). Developing an EBFM framework with analytical decision support tools (e.g., MSE, LCM) requires a comprehensive, inclusive, management forum. Building from the successes of the Columbia Basin Partnership, the NPCC's Ocean Forum and the Columbia Basin Collaborative are existing frameworks that could initiate this process.

Ecosystem management

To impact trophic dynamics in estuarine and marine ecosystems requires understanding the rates and magnitude of impact that predators, prey, and competitors have on salmon population dynamics. The ecosystem structure and dynamics identifies potential management actions and their limits and efficacy.

Predator management

Salmon predators are marine mammals, birds, fishes, and invertebrates, most governed by existing conservation or management structures. Therefore, from a practical standpoint, any proposed predator management action must consider the potential authorization constraints and the fact that these species are naturally occurring components of regional estuary and marine ecosystems. Nonetheless, existing authorizations and permits to manage impacts are currently in place, and as such, can form the basis for initial impact assessment potential.. For example, managing pinnipeds in the estuary and lower Columbia River and avian predators throughout the Columbia River.

A targeted approach to advancing our actionable advice capacity is a direct measure of predation mortality through management experiments; do not let uncertainty be a barrier to action, but incorporate an effectiveness assessment as a critical component of learning by doing. Several research groups have used acoustic tag technologies to estimate survival in segments of the estuary or coastal environments, yet few have lasted longer than a couple years. With a concerted and ongoing tagging project coordinated with ongoing predator management, we would 1) identify the primary predator species in each segment of the estuary and coastal ocean, 2) map out the predation hot spots, where potential management actions could have the largest impact, and 3) quantify the environmental drivers that result in high predator-salmon overlap across years, improving predator management rule curves contributed to MSE and LCM decision support platforms.

Harvest operations

U.S. salmon fisheries in the ocean are governed by the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), as implemented by the Pacific Fishery Management Council for Washington, Oregon, and California waters, and the North Pacific Fishery Management Council in Alaska. Because each species and stock of salmon uses the ocean differently and returns to freshwater at different times, the suite of fisheries that target a particular stock of salmon varies widely. At one extreme are fall Chinook salmon, which are harvested in ocean fisheries from SE Alaska to California, and are also targeted by estuarine and freshwater fisheries. By contrast, Columbia river spring Chinook, steelhead, and sockeye salmon have little ocean harvest, but may be targeted by freshwater fisheries depending on the stock and production type (hatchery/wild).

Harvest levels on a particular stock within a given season depend on the number of adults expected to return to that population that can be harvested within allowable limits. These harvest limits include restrictions due to Endangered Species Act take prohibitions, the Pacific Salmon Treaty (between the U.S. and Canada), tribal treaty fishing rights, and allocation of harvest among different user groups and port areas. Ocean salmon Fishery Management Plans are designed in accordance with international and Federal treaties and laws. Freshwater fisheries for salmon are regulated by an additional set of management regulations, treaties and agreements, resulting in a complex, multi-jurisdictional forum intersecting Tribal, State, and court mediated Federal rights and authorizations.

Bycatch

Most salmon are within 50 m of the surface during their marine residence, consequently they are rarely caught by fisheries targeting non-salmonids, which are typically deeper (e.g., groundfish). However, Chinook salmon reside deeper in the water column than other salmonids, and are incidentally caught by the hake fishery along the West Coast at low rates (<0.01%) (Holland and Martin 2019, Sabal et al. 2023) and the pollock fishery in the Bering Sea and Gulf of Alaska (Barry et al. 2024). A recent analysis (Sabal et al. 2023) indicates that bycatch of Chinook by the hake fishery was highest during warm ocean conditions and at night, as salmon sought cooler waters where hake resided. The hake fishery has taken actions to minimize Chinook bycatch, including restrictions on fishing at night and avoiding bycatch hotspots (Holland and Martin 2019). However, continued ocean warming may decrease the effectiveness of these measures, requiring additional modifications to fishing effort to avoid Chinook salmon (Sabal 2023). The factors that may influence Chinook salmon bycatch in the pollock fishery have not yet been identified. Therefore, impacts of salmon bycatch in the hake and pollock fisheries can be evaluated as a function of fishery effort (location and timing) and climate change (ocean conditions), and are readily amenable to be included in existing or updated fishery specific MSE processes.

Forage fish management

Salmon and their predators exist within a larger marine foodweb. Impacts of predation may rely heavily on the abundance and distribution of alternative prey species, such as forage fish. More precise information on forage fish, both inside the estuary and along the outer coast, could be obtained through comprehensive acoustic, purse seine, and eDNA sampling. Results would improve our understanding and modeling of marine trophic dynamics, especially in nearshore waters, resulting in better management advice.

Some have suggested that altered harvest of forage fish species could itself be a management lever for modifying salmon-predator interactions. Yet fisheries targeting forage fish, especially Pacific sardines, are a small fraction of their former size. In fact, the primary directed fishery for Pacific sardine has been closed since 2015, suggesting that options to manage forage fish to optimize salmon survival may be limited.

Currently, many coastal pelagic fisheries only provide fish for the live bait trade and most of this harvest is well below allowable limits. One exception is the market squid fishery, which accounts for the majority (>90%) of coastal pelagic landings and revenues, most of which occurs in southern and central California. For all coastal pelagic species, managed federally or in state waters, harvest in Oregon and Washington waters is low and unlikely to have a major negative effect on salmon. However, if abundance of these species rebounds to the point where targeted fisheries are initiated, there may be ways to manage the fishery to optimize the predation-related benefit of having large numbers of forage fish to act as alternative prey for salmon predators. In the meantime, any management outside of harvest controls that may assist the recovery of forage fish populations could have the added benefit of lowering salmon predation rates.

Hatchery operations

On-going research to improve public hatchery systems in the Columbia River Basin addresses changes to age, growth rates, timing and location of releases, and other factors to improve survival and reduce ecological and genetic risks. Resulting improvements at any given hatchery will most directly affect the performance of released fish, and potentially their offspring. By contrast, ecological effects in the estuary and ocean will most strongly reflect the aggregate effect of the larger hatchery system that includes tens of millions of smolts, multiple species and diversity of life history traits. Therefore, improvements to potential ecosystem scale impacts to wild fish by hatchery production in the Columbia River will require coordinated efforts throughout Columbia and Snake River Basin hatchery complexes.

Management action options must balance per facility operational changes with regional operational coordination. That is, a Columbia River basin-wide strategy to minimize the adverse ecosystem impacts of hatchery operations must differentiate between the aggregate impact of per facility operational changes (releasing fish in certain areas based on the purpose of the program (e.g., SAFE production), or using weirs to keep hatchery fish out of certain areas, or altering a release strategy (e.g., switching from yearling fall Chinook to subyearling)) with a system-wide collaboration to manage release numbers and timing by estuary and nearshore ecosystem health projections. Only through the application of decision support systems does the management community have the power to forecast complex implementation strategies and evaluate the costs and benefits of implementation across the multiple scales, jurisdictions, and program mandates.

Decision support systems

Lifecycle modeling

Decision support systems, both the process of building them and their application, are meant as an evaluation framework to guide management action prioritization, but also to manage the development of knowledge (research and monitoring) that frames the decision support tools themselves.. Salmonid life cycle models, one type of decision support tool, are comprehensive in two ways: 1) they represent and integrate effects across the entire lifecycle of salmonids; and, 2) a multitude of management actions and climate change can be applied either separately or in combination at each applicable life stage. They can include effects of physical habitat, environmental conditions, trophic dynamics, population density, and other processes regulating populations, and the effects can be characterized in life cycle models in simple or complex functional relationships that transition fishes from one life stage, time step, or location to the next.

Salmonid lifecycle models have been built for several interior Columbia River Basin populations and have been previously applied to evaluate effects of multiple management questions and climate change (e.g., Pess and Jordan (2019); Zabel and Jordan (2020); Crozier et al. (2021)).

Lifecycle models are often not built and then kept static during application. Models can continually incorporate new and updated information, accounting for changing environmental conditions or management actions. In this way, advances in models or knowledge in one life stage, such as the Columbia River estuary or nearshore ocean, will be integrated into existing lifecycle models. Due to the interconnected nature of lifecycle models (across salmon life stages), these model updates can influence dynamics throughout the lifecycle, highlighting the importance of refining all life stages in lifecycle models, not just those will current management applications.

Adaptive management

Developing and implementing a decision structure that could deal with the scale of the issues surrounding rebuilding salmon stocks of the Columbia River basin should be based on the principles of adaptive management. Adaptive management is a structured, iterative process of action implementation that formally incorporates uncertainty and learning over time (Williams et al. 2009). Adaptive management has been used to guide large-scale ecosystem restoration programs (Chesapeake Bay, the Florida Everglades, the Great Barrier Reef, and the Elwha River; Peters et al. 2014, Diefenderfer et al. 2021). Integrating our knowledge of estuary and ocean salmon ecology with current and future management regimes will be a long-term process of incorporating new knowledge and practices despite considerable, and ongoing, uncertainty. Adaptive management strategies are ideally suited for this decision environment.

Whenever advocating for an adaptive management based approach, it is critical to recognize that many adaptive management programs have not been successful and that their route of failure typically follows one of three primary paths. First, a lack of the human and financial resources for the monitoring needed to carry out large-scale actions in the context of interim performance metrics and regular, structured adjustments. Second, the need to admit and embrace uncertainty in making policy choices. Lastly, a lack of individuals willing to do all the hard work necessary to plan and implement new and complex management programs (Walters, 2007).

Successfully implementing adaptive management based ocean and estuary research and actions strategies is necessary to inform decision making on the scale of rebuilding Columbia basin salmon and steelhead stocks. Adaptive management provides the ability to incorporate all types of human impacts – climate change, habitat degradation, hydropower development, harvest, and hatcheries – and to evaluate the effects of management actions using a suite of viable salmonid population metrics (VSP: abundance, productivity, spatial structure, and diversity; McElhany et al. 2000, Peters et al. 2014). An adaptive management framework is also a necessary component of a co-stewardship based research and decision support tool development process. Testing, learning, and adapting is an inherently collaborative process that requires and facilitates co-stewardship as all parties play an active role in the learning and resultant planning.

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