Fish and Fisheries

WILEY

FISH and FISHERIES

ORIGINAL ARTICLE OPEN ACCESS

A Safe Operating Space for Salmon Watersheds Under Rapid Climate Change

Jonathan W. Moore[1,2] | Marta E. Ulaski[1] | Kyle L. Wilson[2,3] | Tara G. Martin[4] | Spencer Dakin Kuiper[1] | Stephanie J. Peacock[5] | Douglas C. Braun[2,6] | Sean M. Naman[2,6] | Kara J. Pitman[1] | Andrea J. Reid[7] | Jordan S. Rosenfeld[8] | Nigel C. Sainsbury[1] | Samantha M. Wilson[2] | Benjamin J. Zdasiuk[1]

[1]Earth to Ocean Research Group, Simon Fraser University, Burnaby, British Columbia, Canada | [2]Aquatic Research Cooperative Institute, Simon Fraser University, Burnaby, British Columbia, Canada | [3]Central Coast Indigenous Resource Alliance, Vancouver, British Columbia, Canada | [4]Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, British Columbia, Canada | [5]Pacific Salmon Foundation, Vancouver, British Columbia, Canada | [6]Fisheries and Oceans Canada, Vancouver, British Columbia, Canada | [7]Centre for Indigenous Fisheries, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, British Columbia, Canada | [8]Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, British Columbia, Canada

Correspondence: Jonathan W. Moore (jwmoore@sfu.ca)

Received: 21 March 2025 | **Revised:** 30 August 2025 | **Accepted:** 6 September 2025

Funding: This paper arose in part from conversations as part of the Watershed Futures Initiative, an initiative supported by the British Columbia Restoration and Innovation Fund, Fisheries and Oceans Canada, the MakeWay Foundation, the Sitka Foundation, the Wilburforce Foundation, Natural Sciences and Engineering Research Council of Canada Discovery Grants to Jonathan W. Moore and Tara G. Martin, and Liber Ero Research Chairs to Jonathan W. Moore and Tara G. Martin.

Keywords: climate adaptation | cumulative effects | mitigation | Pacific salmon | resilience | social-ecological system

ABSTRACT

Climate change and local pressures are eroding the health and performance of many watersheds and their freshwater ecosystems, pushing these complex social-ecological systems to the boundaries of their safe operating space. Here, we offer a synthetic perspective on the downscaled application of the safe operating space concept to inform the stewardship of watersheds in this time of rapid climate change, with particular focus on watersheds that support coldwater migratory fishes such as Pacific salmon. First, we review the safe operating space concept as it applies to salmon watersheds as social-ecological systems. Salmon watersheds, and the benefits they provide for diverse peoples, are under enormous cumulative pressure from climate change as well as local activities such as forestry, urbanisation, mining and agriculture. We identify four general syndromes of dual local and climate pressures. For example, local pressures, such as the removal of riparian vegetation that shades streams, can exacerbate climate warming of water temperatures. Furthermore, extractive industries can damage or destroy future habitats and thus erode adaptive capacity. As an illustrative example of how the safe operating space concept can be operationalised, we assess alternative plausible watershed futures of land use and climate change scenarios and salmon performance. Collectively, this work showcases tangible options for local management to help give salmon watersheds the time and space to cope with climate change. More broadly, while there is a global need to address climate change, local watershed management is a key component of pathways towards freshwater sustainability and their services for humanity.

1 | Introduction

Watersheds and their freshwater ecosystems are critical for life on Earth and provide invaluable ecosystem services, but are heavily pressured by the cumulative impacts of climate change and local human activities (Falkenmark et al. 2019; Rockström and Karlberg 2010). For example, global inland fisheries catch over 17 million tonnes of fish each year, providing livelihoods and food security for millions of people (Ainsworth et al. 2023). However, watersheds and their freshwaters are harmed by various local land-use practices such as mining, forestry, agriculture and urban development (Allan 2004; Reid et al. 2019). Climate change is further warming waters and changing flow regimes (IPCC (Intergovernmental Panel on Climate Change) 2022). Indeed, global assessments indicate that 25% of freshwater biodiversity is threatened with extinction (Sayer et al. 2025).

Watersheds are influenced by social and natural processes that span global to local scales. While there is a global imperative to reduce greenhouse gas emissions, the management of human activities in watersheds generally occurs at local scales. Global climate change affects local watershed functioning through changes in temperature and precipitation and may alter the effectiveness of local-scale management actions. Pragmatic constructs are urgently needed that link global climate and local pressures to inform the limitations of, or opportunities for, local conservation and management actions in an era of climate change (Moore and Schindler 2022).

Downscaled versions of the 'safe operating space' (SOS) concept could provide a pragmatic construct to guide proactive management. The concept of 'safe operating space' (SOS) integrates the combined risks posed by multiple pressures on Earth's complex ecosystems and the benefits provided for humanity (Rockström et al. 2009). The SOS boundary delineates the transition between the normal range of variation and compromised ecosystem performance or a tipping point to an alternate ecosystem state. The SOS concept can be downscaled to inform local management by aggregating pressures into two dimensions: (1) Local pressures that are under local management control, such as land use; (2) External pressures that are outside of local management control, such as global climate change (Scheffer et al. 2015). These local and external pressures interact to determine the net impact on the ecosystem. For example, many streams are shifting from perennial to intermittent flow states in Mediterranean regions, driven by a combination of climate change, water extraction and land use (Carlson et al. 2023). As well, warming lake temperatures from the combined effects of climate change and local habitat degradation can decrease the productivity of coldwater fishes and their fisheries (Carpenter et al. 2017; Hansen et al. 2019). The SOS concept may provide a powerful framework to catalyse effective local management of watersheds into the changing future (Carpenter et al. 2017; Green et al. 2017; Scheffer et al. 2015).

Here, we focus on the North American watersheds that support migratory Pacific salmon (*Oncorhynchus* spp.) and suggest these well-studied social-ecological systems provide lessons germane to watershed management around the world. Diadromous fishes, like Pacific salmon, connect ocean and inland freshwaters, are ecologically and culturally important and contain many examples of conservation failures and some successes. Salmon ecosystems are being pressured by climate change and varying local human activities across their extensive range (Ulaski et al. 2025), resulting in a variety of states and trajectories (Griffiths et al. 2014). While a few salmon stocks are thriving (Hilborn et al. 2003) or recovering (Pess et al. 2024), most populations of most species appear to be declining in abundance or productivity (e.g., Chinook salmon, (Atlas et al. 2023)), and other regions are defined by complete loss and harm. For example, 29% of > 1000 historical unique salmon populations have been extirpated since European contact in the western contiguous United States (Gustafson et al. 2007). Salmon declines cause loss of diverse benefits to people and impoverish human-salmon relationships. Despite major investments (Bilby et al. 2024), most salmon watersheds are struggling and there is an urgent need to enable positive actions for watersheds in a rapidly changing world.

We apply the SOS concept to watersheds that support wild migratory Pacific salmon as an integrative framework to guide local management given ongoing climate change. First, we overview the SOS concept as it applies to salmon-bearing watersheds (Section 2). We then synthesise the literature to examine how dual pressures of global climate change and local land use activities can harm salmon and their habitats (Section 3). We offer four general syndromes of these linked dual pressures, each with their own management challenges and opportunities. Last, we illustrate how the SOS concept can be operationalised into collaborative decision-support tools with forward-looking simulations of salmon performance under scenarios of local land use and global climate changes (Section 4). Collectively, this integrative work illustrates how contemporary environmental policies and practices, built to enable industrial activities and based on the 'climate normal' past, are likely insufficient to keep salmon watersheds in their SOS under climate change. However, the salmon SOS framework also identifies tangible watershed management and policy options and sustainable paths forward with broad relevance to climate resilience (Section 5).

2 | Applying the Safe Operating Space Concept to Salmon Watersheds

The SOS of a salmon watershed can be characterised as its ability to provide sufficient social and ecological benefits given cumulative pressures from local activities and climate change (Figure 1). Intact and healthy watersheds allow salmon populations to thrive and, in turn, provide diverse benefits for people and ecosystems (Figure 1A). Salmon are cultural keystone species and viewed as kin by many Indigenous Peoples (Carothers et al. 2021; Garibaldi and Turner 2004; Reid et al. 2022). Productive salmon populations also sustain fisheries that support economies, food security, cultures and livelihoods (Carothers et al. 2021; Donkersloot et al. 2020; Nesbitt and Moore 2016; Reid et al. 2022; Schindler et al. 2010). Healthy watersheds allow for salmon populations to support diverse wildlife, including killer whales and grizzly bears (Ford and Ellis 2006; Levi et al. 2012). Protected watersheds can also provide natural spaces that promote human well-being, forests that sequester carbon and clean water for consumption (Rahr et al. 2025). Local human activities and climate change impacts, together or in isolation, can pressure salmon watersheds and their

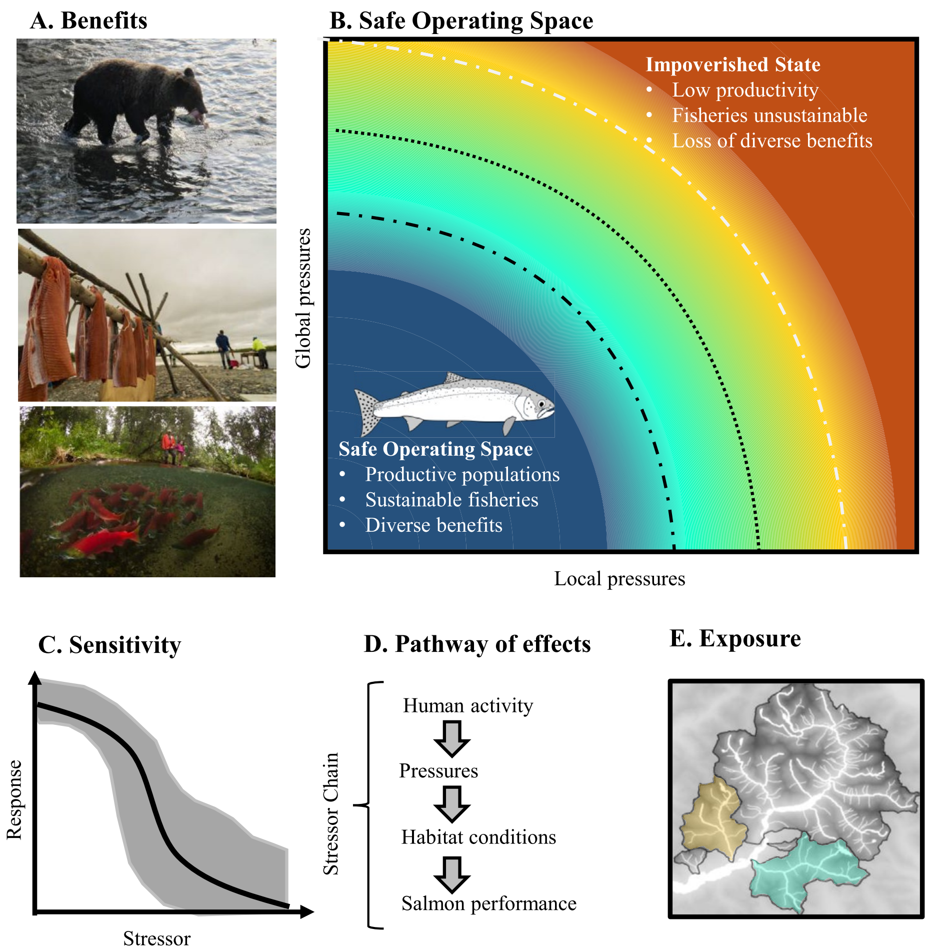

FIGURE 1 | The salmon safe operating space (SOS). (A) Healthy salmon watersheds provide diverse benefits. Pictures by J.W. Moore, J. Monroe and J. Armstrong, top to bottom. (B) A theoretical SOS surface for salmon. The z-axis is the overall performance of the system (e.g., salmon population productivity), ranging from thriving (dark blue) to impoverished (umber). The boundaries of the SOS could be risk-adverse (black dashed line), moderate (black dotted), or risk-tolerant (white dashed). (C) The sensitivity of the system is defined by stressor-response relationships. (D) The SOS is a multi-dimensional surface arising from multiple stressor chains from human activities to pressures to habitat conditions to salmon performance. (E) Different salmon watersheds may have different performance surfaces and also will be situated in different parts of their performance surfaces due to varied exposure to pressures.

component pieces beyond the bounds of typical variation and into a state of impoverishment, with various harms for people and ecosystems. For example, a salmon watershed may be in a moderate state of health, with intermediate pressures from local activities and climate change. In time, under moderate to high emissions scenarios, climate change alone may push the watershed to its SOS limits. On the other hand, under low emissions scenarios, climate change alone may only slightly increase the probability that the system is pushed to its SOS limits. Local actions could either exacerbate or ameliorate this trajectory. Thus, different combinations of local and global pressures will produce varied states and trajectories of salmon watersheds (Figure 1).

The literature uses diverse terms to describe human impacts on ecosystems. Any given harm is caused by a chain of causal relations, a pathways of effects' or 'stressor chain' (Rosenfeld et al. 2022). Harm originates from human 'activities' (e.g., forestry) that directly result in 'pressures' (e.g., loss of riparian forest) that change 'habitat conditions' (e.g., increased water temperatures) that influence 'performance' of the focal ecosystem component, in this case salmon (e.g., survival). The term 'stressor' can be broadly applied to any factor within the stressor chain that drives changes in performance, including the human activity, the pressure, or the altered habitat condition.

We focus our consideration of the SOS at the scale of major watersheds or aggregates of smaller watersheds that support a salmon stock complex or meta-population. Conceptually, the SOS can be viewed as a manifestation of the ecological niche, that is, an n-dimensional hypervolume where each axis represents a different stressor (pH, temperature, etc.) that collectively define the performance of the system (e.g., salmon population growth) (Rosenfeld et al. 2022). We refer to this as the 'ecological SOS'. However, to facilitate its applicability, the performance surface can instead be defined by the emergent outcomes from various human pressures that are aggregated to two dimensions: local (e.g., forestry, mining) and global (e.g., climate change). We refer to this as the 'management SOS' and is the primary focus of this paper.

The definition of the performance surface deserves care and inclusiveness because it is inherently intertwined with the values and goals of diverse rightsholders and stakeholders. For example, a performance surface could consider performance metrics of salmon populations, salmon fisheries or the role of salmon in supporting important wildlife (e.g., (Levi et al. 2012)). From a social perspective, the performance surface could be defined by the health of relationships between salmon and people, which reflect provisioning and cultural services (e.g., (Donkersloot et al. 2020)). Further, time horizons for performance should align with community values that could range from a short planning window to intergenerational stewardship.

The boundaries of the SOS can be informed by science and knowledge, but they are also inherently based on values related to risk tolerance and levels of acceptable harm. The boundaries of the SOS delineate safe from unsafe outcomes to inform management and decision-making by, for example, determining the suite of permitted activities that might allow a salmon watershed to remain in its SOS despite inherent variability and non-stationarity (Johnson 2013). In a typical quantitative application, ecological models can be used to characterise the performance surface, and the boundary might then be defined as the parameter space whereby population viability is jeopardised. Rather than typical fisheries management benchmarks that just guide harvest such as in maximum sustainable yield approaches, the SOS boundaries can provide a holistic consideration of the acceptable limits of performance for salmon watersheds across multiple pressures. Importantly, different peoples will likely have different ideas of what level of performance, or conversely, risk, is acceptable (different dashed lines on Figure 1). For example, the abundance of salmon that makes a population viable in the short term may be substantially less than the abundance and diversity that enables diverse benefits, deep cultural connections and equity (Donkersloot et al. 2020; Lamb et al. 2023; Raworth 2017). Accordingly, SOS boundaries should not be considered as one-size-fits-all thresholds of precise impact, but rather as local boundaries of socially acceptable risk. Inclusive collaborative processes with diverse communities in defining performance metrics and setting SOS boundaries (Adams, Tulloch, et al. 2023; Martin et al. 2012) can embrace knowledge and values pluralism to navigate power asymmetries and advance recognitional and procedural equity for social justice (Pascual et al. 2023).

3 | Synthesis of Global and Local Pressures on Salmon Watersheds

3.1 | How Salmon Watersheds Work

Salmon watersheds are complex social-ecological systems that are incredibly varied across the vast range of Pacific salmon. Anadromous salmon rely on marine habitats for feeding and growing, and freshwater habitats in watersheds for spawning, incubation, and rearing. Watershed physical processes of movements of water, sediment, wood and other materials (Montgomery 1999) generate dynamic mosaics of the diverse habitats required by salmon to complete their freshwater life cycles (Bisson et al. 2009; Brennan et al. 2019; Stanford et al. 2005). Salmon are generally considered a 'cool-water' species that are harmed by excessively warm water temperatures. Thus, salmon can be strongly influenced by dynamic thermal riverscapes that are in turn controlled by climate and weather, watershed attributes, stream flow, groundwater and human activities (Ebersole et al. 2020; Leach et al. 2023). Salmon are also strongly influenced by the timing and magnitude of water flows that control habitat suitability and access (Beechie, Buhle, et al. 2006; Ward et al. 2015). Thus, the SOS of salmon watersheds is underpinned by watersheds with functioning hydrologic and geomorphic processes that generate and maintain connectivity, complexity, dynamics and diversity of suitable aquatic habitats. Diverse and dynamic habitat conditions underpin the vast trait and genetic diversity of salmon. Through providing a diverse and dynamic set of options, akin to a diverse financial portfolio, diverse salmon habitats and populations can dampen risk and provide adaptive capacity and resilience (Brennan et al. 2019; Hilborn et al. 2003; Schindler et al. 2010).

Salmon watersheds vary in their local human cultures, economies, values, governance systems, infrastructure and activities that connect salmon and people (Atlas et al. 2021). Fisheries are important connections between salmon and people and may operate across the migratory routes and salmon and thus within, or external to, watershed boundaries. Salmon fisheries range from industrial fisheries that harvest multiple stocks as they comingle along ocean migration routes, recreational or sport fisheries along coasts and in freshwaters, to local coastal and inland Indigenous fisheries (which can include so-called 'food, social and ceremonial' fisheries, as well as commercial interests), as well as subsistence fisheries for other local communities. Even as salmon watersheds vary enormously in their environment and geography across their vast range, they are also interwoven with a diverse social and cultural human fabric.

3.2 | Shifting Salmon Watersheds

Climate change and the cumulative impacts of various local human activities challenge salmon watersheds across their vast range in western North America (Figure 2). In Arctic rivers of northern Alaska and Canada, salmon spawn in the emerging pockets of groundwater that stay unfrozen. In desert rivers in California, salmon huddle in cool-water refugia during the hot summer months. Repeatedly, focal analyses suggest that the trajectories of salmon populations are generally driven by some combination of various local and global pressures (Cunningham et al. 2018; Murdoch et al. 2024; Nehlsen et al. 1991; Wilson et al. 2022). There is generally 'no smoking gun', but rather a 'death by a thousand cuts' (Ulaski et al. 2025). Human land-use pressure is generally greater in lower latitude than higher latitude regions, but there are many localised hotspots of human land-use pressures across the North American salmon range (Figure 2C).

Human-caused climate change is profoundly shifting salmon ecosystems (Crozier and Siegel 2023). Across the range of salmon, the climate is warming faster at higher latitudes, while lower latitude ranges are generally already hot (Figure 2A). Anthropogenic climate change is also altering flow regimes. Many northern watersheds are predicted to experience an

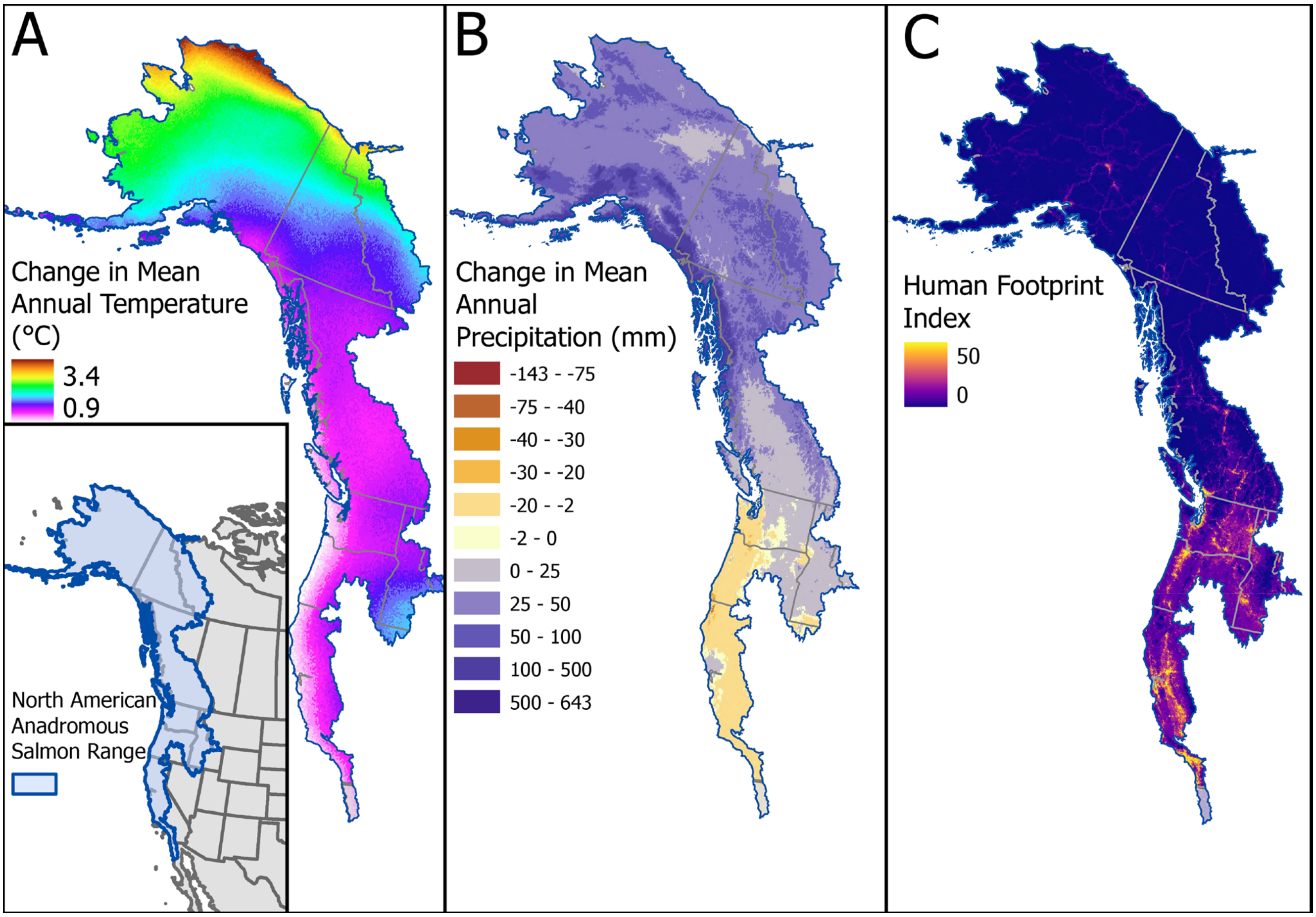

FIGURE 2 | Salmon stressors and climate change across their range in North America. (A) Predicted changes in mean annual temperature between climate normal 1961–1990 and projected values for mean 2011–2040 under climate emission scenario SSP2-4.5 (Mahony et al. 2022). (B) Predicted changes in mean annual precipitation between climate normal 1961–1990 and projected values for mean 2011–2040 under scenario SSP2-4.5. (C) Human footprint index, a composite index of land-use alteration (Mu et al. 2022).

increase in total precipitation (Figure 2B) that can, in combination with snowfall shifts to rain as well as extreme storms, lead to more frequent flooding that scour incubating salmon embryos (Sloat et al. 2017). In more southern arid watersheds, forecasted decreases in total precipitation and snowpack (Figure 2B) are predicted to increase summer droughts and reduce low summer flows (Mantua et al. 2010), which can impair the survival of stream-rearing juvenile salmon (Warkentin et al. 2022). Climate change is also altering marine environments that support Pacific salmon. For example, the 2014–2016 marine heat wave in the California Current, the 'Blob', reduced copepod and euphausiid biomass and decreased marine survival of salmon in the region (Peterson et al. 2017). Warming ocean temperatures are contracting the southern range of salmon in the Pacific Ocean, pushing this boundary northwards (Langan et al. 2024). Climate change is also fundamentally transforming salmon watersheds—glacier loss is reducing summer cooling water flows but also is opening up future streams and lakes (Pitman et al. 2020, 2021), and sea-level rise could inundate estuaries that otherwise provide nursery habitats for outmigrating smolts (Davis et al. 2022; Flitcroft et al. 2013). These different symptoms of climate are being expressed across the vast range of salmon that have co-occurring human land-use pressures (Figure 2C).

3.3 | Syndromes of Combined Impacts of Global Climate Change and Local Watershed Pressures

We present four different syndromes of the combined impacts of global climate change and local watershed pressures (Figure 3). These syndromes are not exhaustive nor exclusive. These syndromes offer simplifying and generalisable categories of the different combined impacts of climate and local watershed pressures and their associated management challenges and opportunities.

3.3.1 | Shared Local Stressor (Climate Amplification Syndrome)

Description: Climate change and local pressure affect the same habitat condition stressor to cause cumulative harm (Figure 3A).

Management challenge: Ecosystem harm from inadequate management of a local pressure is exacerbated by climate change.

Management opportunity: Strengthened management of the local pressure can decrease susceptibility of habitat stressor to climate change.

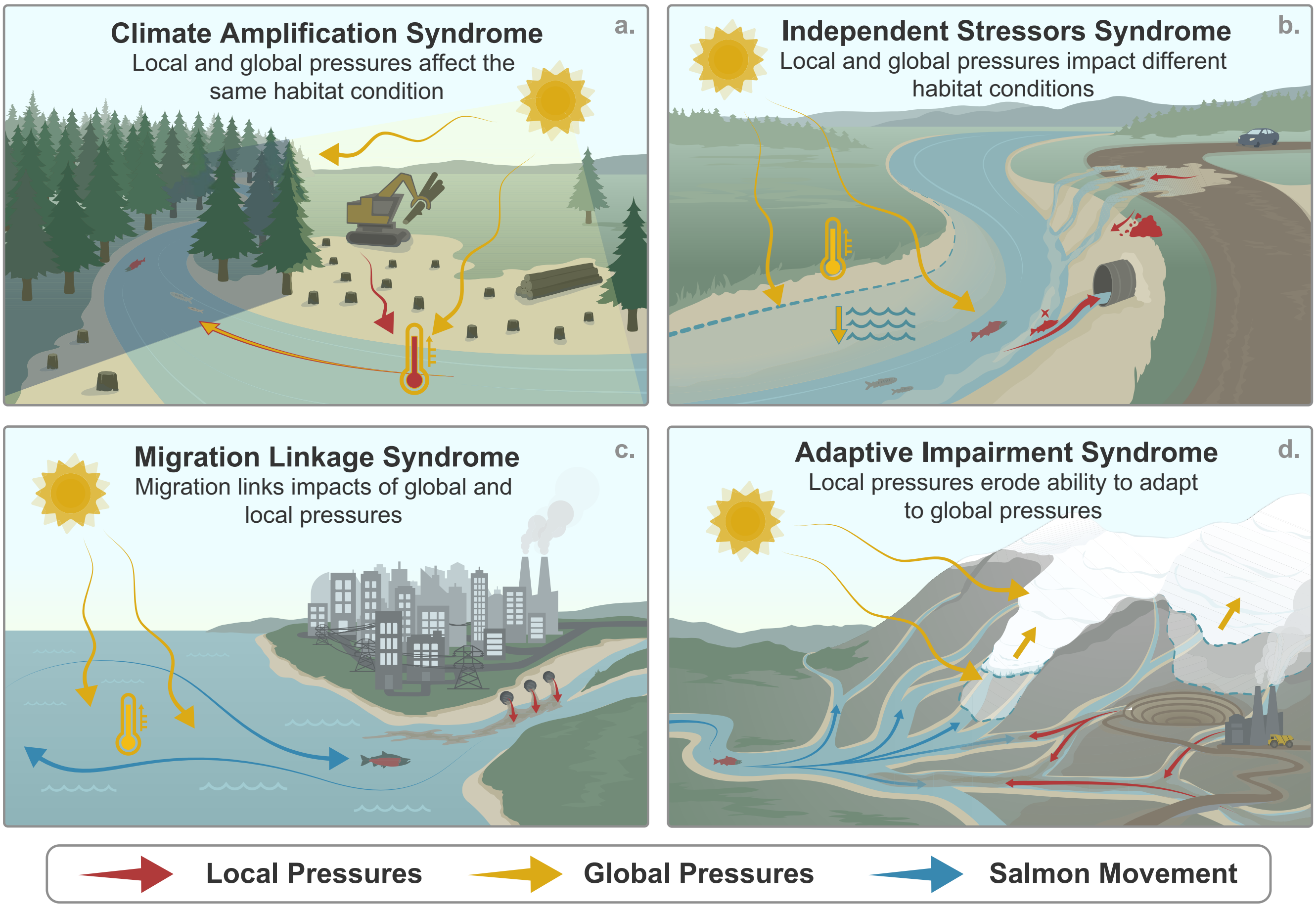

FIGURE 3 | Four syndromes that describe different ways that global pressures and local land use pressures can combine to influence the trajectories of salmon ecosystems: (A) the Climate Amplification Syndrome, (B) the Independent Stressors Syndrome, (C) the Migration Linkage Syndrome, and (D) the Adaptive Impairment Syndrome.

Global climate pressures can combine with local pressures to cumulatively impact the same habitat condition stressor (Figure 3A, Table 1). If global and local pressures push salmon watersheds along the same pressure-response curve, salmon populations may become increasingly compromised by even incremental increases in either pressure. For example, major human activities in salmon watersheds—agriculture (Allan 2004), forestry (Naman et al. 2024) and mining (Sergeant et al. 2022)—share key symptoms with climate change: higher stream temperatures, flashier high flows and lower summer flows (Table 1). This syndrome of local and global impacts on a shared stressor has profound implications for watershed management given climate change. For instance, if regulations are ineffective at minimising the degradation of habitat conditions, the addition of climate change will amplify these inadequacies and result in harm to salmon. Even historically effective regulations, if based on past climate-normal conditions, risk failing to offer sufficient protections given ongoing climate change.

One key example of local and global pressures impacting the same habitat stressor is the impact of riparian forest loss on water temperatures. Many salmon watersheds have experienced extensive loss of riparian habitat from riparian forestry, agriculture and wildfires. Riparian forest loss decreases shading, leading to warmer water temperatures of upwards of 5°C in some situations (Cunningham et al. 2023; Moore and Richardson 2012; Naman et al. 2024). Extensive forestry can also decrease the residence time of water in snow and soil reservoirs, making stream flows flashier and, in some cases, contributing to reduced summer base flows and potentially increased sensitivity to air temperatures (Gronsdahl et al. 2019; Naman et al. 2024). Thus, riparian forest loss can exacerbate the impacts of higher summer air temperatures from global climate change on stream temperature and flow.

Conversely, strengthening local riparian management can contribute to the mitigation of climate pressures and thereby help maintain salmon watersheds within their SOS. In northeast Oregon, for example, local restoration of riparian habitats and their shading is expected to counteract the impacts of substantial warming of air temperatures (Wondzell et al. 2019). While local management of riparian forests does not directly address global climate pressures, intact riparian forests can mitigate some impacts of increasing air temperatures by providing shade and decreasing the climate sensitivity of streams (Cristea and Burges 2010; Fuller et al. 2022; Justice et al. 2017; Lawrence et al. 2014; Wondzell et al. 2019).

TABLE 1 | Climate change and local industry activities (forestry, mining, agriculture) and their impacts on local habitat conditions. Major categories of land use activities could either have impacts that are the same as those from climate change (exacerbating, red and orange below), no impacts (grey). See main text for references.

Climate change symptom	Description	Forestry	Mining	Agriculture
Warming water temperatures	Warmer air temperatures and changing flows are warming water temperatures. Excessively warm water temperatures can decrease salmon health. Mass mortality of salmon due to hot water is already happening in some years and rivers.	Forestry practices that reduce riparian vegetation and promote clear cutting can increase water temperatures 2°C–5°C.	Mining may lead to increased water temperature from water withdrawals and changes to the flow regime.	Agricultural practices that remove riparian vegetation can increase water temperatures.
Decreasing summer flows	Shifts from snow to rain are decreasing water storage and lowering summer water flows in some regions. Low summer flows can decrease the amount of rearing habitat for young salmon and potentially decrease access to spawning habitats for adult salmon.	Clear cut forestry practices can decrease summer freshwater flows 10–40 years following harvest.	Mining operations often use a large amount of water and can decrease low summer flows.	Water withdrawals for agriculture can be a major contributor to lower summer flows.
Increasing fall and winter floods	Shifts in precipitation are increasing flood severity and frequency. Floods can present migration barriers and scour out or bury salmon eggs.	Clear cut forestry practices increase flood severity and frequency.	Relatively unknown.	Some agricultural practices, such as drainage tiles, can directly increase run-off and flashiness; dikes and other infrastructure also limit salmon access to off-channel flow refugia.
Extensive evidence of human activities exacerbating same climate change symptom				
Some evidence of exacerbating impacts				
Little evidence or inconsistent				

3.3.2 | Global Pressure Adding Additional Local Stressors (Independent Stressors Syndrome)

Description: Global climate change and local pressures contribute distinct and unrelated stressors that cause cumulative harm (Figure 3B).

Management challenge: Climate pressures will continue to contribute to cumulative harm to salmon watersheds that are already challenged by local pressures and thus elevate risks of pushing them out of their SOS. Regulation and local management actions have little capacity to directly address global pressures.

Management opportunity: Strengthened local management may not be able to address climate pressures, but it can reduce the cumulative net impacts on salmon watersheds.

The cumulative harms of both local and global climate change, even if unrelated and incremental, combine to affect salmon watersheds (Figure 3B). For instance, salmon watersheds among highly pressured regions, such as California's Central Valley, are subjected to extensive land-use changes including habitat loss, severed connectivity, invasive species and pollution (Munsch et al. 2022). Meanwhile, climate change pressures also increase local stressors including excessively hot water temperatures and droughts that may kill adult salmon and reduce juvenile salmon rearing capacity.

This syndrome reveals that local management actions will not address climate-associated impacts head-on, but they can reduce the cumulative net impact on salmon and their watersheds. The effective management of cumulative effects is a major challenge for this and the other syndromes, as current policies generally implicitly or explicitly enable cumulative incremental harm to salmon watersheds (Ulaski et al. 2025). There is thus a need for planning and policy tools that protect local salmon ecosystems from cumulative effects (Ulaski et al. 2025). Addressing local stressors will provide cumulative benefits for salmon that could help keep salmon within their SOS despite climate change.

3.3.3 | Migration Links Impacts of Global and Local Pressures (Migration Linkage Syndrome)

Description: In addition to the local pressures they face in their home watersheds, migration exposes salmon to additional global pressures occurring in the ocean (Figure 3C).

Management problem: Regulation of individual pressures, either local or in the shared ocean, based on past salmon productivity may no longer be sufficiently protective to keep salmon watersheds in their SOS.

Management opportunity: Strengthened international management of activities that affect the ocean as well as local management of local pressures can help mitigate impacts of climate change.

Studies have repeatedly found that both marine and freshwater pressures can jointly regulate salmon populations (Figure 3C) (Cunningham et al. 2018; Ward et al. 2015; Wilson et al. 2022). Indeed, salmon are exposed to a myriad of local watershed and marine pressures across their migratory life cycle (Ulaski et al. 2025). While beyond watershed boundaries, marine pressures can include the marine symptoms of climate change, industrial fisheries and competition with co-occurring salmon (Connors et al. 2024; Langan et al. 2024). International treaties that oversee the activities that impact the shared ocean commons, such as the Pacific Salmon Treaty, should be critically evaluated and revised as needed so they are robust to oncoming climate impacts on salmon. This syndrome illuminates that addressing local pressures will not address key marine pressures, but it can provide additional cumulative benefits for salmon that help keep salmon within their SOS.

3.3.4 | Eroding Adaptive Capacity (Adaptive Impairment Syndrome)

Description: Local pressures damage the adaptive capacity of salmon watersheds and thus decrease their ability to cope with oncoming climate change (Figure 3D).

Management problem: The adaptive capacity of salmon watersheds is insufficiently recognised and protected by environmental policies.

Management opportunity: Strategically identify and protect or restore important dimensions of adaptive capacity that can include genetic diversity, habitat portfolios and future key habitats.

Local pressures can erode the adaptive capacity and climate resilience of salmon watersheds (Figure 3D). The adaptive capacity of salmon watersheds has many different dimensions and hierarchical scales of organisation that range from habitat mosaics to life-history diversity to genetic diversity (Healey 2009; Hilborn et al. 2003; Schindler et al. 2008). Thus, this syndrome is broad; indeed, in the broadest sense, all of the previous three syndromes can also erode adaptive capacity if they decrease habitat or salmon population diversity, productivity, or abundance. The adaptive capacity of salmon watersheds is strongly influenced by local watershed pressures. For example, while hatchery practices are incredibly varied, hatcheries can erode genetic diversity and thus adaptive capacity of wild salmon stock complexes (Naish et al. 2007). The destruction or degradation of salmon habitats and populations removes potentially important future options from the portfolio (Anderson et al. 2015; Carlson and Satterthwaite 2011; Moore et al. 2010; Munsch et al. 2022). Landscape-level habitat protection within priority salmon landscapes that contain functioning watersheds and diverse habitats and salmon can help conserve the adaptive capacity of salmon watersheds (Griffiths et al. 2014; Schindler et al. 2008).

There are also local opportunities to protect not just current salmon habitats, but also future salmon habitats, given oncoming habitat transformations due to climate change. Climate change is driving expansion and contraction of the suitability of habitats, such as with sea-level rise (Davis et al. 2022; Flitcroft et al. 2013), glacier retreat (Pitman et al. 2020, 2021), Arctic warming (Dunmall et al. 2024) and warming of fresh waters (Iacarella and Weller 2024). Local pressures can damage habitats that will be important in the future. For example, climate change-induced glacier retreat is creating new rivers and lakes that provide future habitat for salmon in the Alaska/British Columbia (BC) transboundary region (Pitman et al. 2021). However, mining may degrade these future salmon habitats unless there is policy reform of mining legislation and proactive habitat protections such as via Indigenous Protected Conserved Areas (Moore et al. 2023). Similarly, impassable dams on California rivers block Chinook salmon access to cool thermal refuges in higher elevations that will be increasingly important in the warming future (FitzGerald et al. 2021). Conversely, dam removal can lead to rapid increases in salmon abundance and life-history diversity (Pess et al. 2024). These and other examples (Bottom et al. 2005; Finn et al. 2024) showcase opportunities for forward-looking protection or large-scale restoration to support future opportunities for salmon given climate change.

4 | Scenarios of Climate Change and Watershed Land Use

The SOS concept can be incorporated into decision-support tools to guide watershed management of local pressures and fisheries in a warming world. Future scenarios can be used, not necessarily to provide predict-and-prescribe support, but rather to provide strategic guidance to identify robust management actions and policies (Schindler and Hilborn 2015). For example, restoration approaches in salmon watersheds can target different locations to maximise benefit with future climate warming (Battin et al. 2007; Beechie, Imaki, et al. 2006). A diversity of modelling approaches and tools has been developed and used to explore watershed management options given climate change and other watershed pressures (e.g., (Adams, Tulloch, et al. 2023; Beechie, Imaki, et al. 2006; Fuller et al. 2024)).

4.1 | Methods

As an illustrative example, we explore a Climate Amplification Syndrome and its impact on the SOS of a hypothetical salmon watershed. In this example, forestry land-use activity (local pressure) combines with warming air temperatures (global pressure) to impact water temperatures and ultimately salmon performance. Using the concepts of the Climate Amplification Syndrome (Figure 3A, Table 1), we developed a simulation model to examine how a semelparous fish population performs into the future given scenarios of climate change and watershed management through 2100 (Figure 4). The specific model formulation and parameters were based on a hypothetical sockeye salmon population, with parameters sourced from studies of small to mid-sized watersheds of interior BC, Canada (Table S1). The fish population follows density dependent population dynamics with stochasticity and a local fishery with abundance-based harvest rules. The population suffers mortality during the post-fishery upriver adult migration if water temperatures are too hot (Figure 4C). The model took a simple approach to water temperatures; riparian harvest warmed waters in an additive manner, and water temperature was related to air temperature in a linear manner with a static climate sensitivity parameter. Rates and magnitudes of air temperature warming depend on the greenhouse gas emissions scenarios, ranging from low (SSP1-2.6) to high 'business as usual' scenarios (SSP5-8.5). We assessed performance as an integrated function that equally weighted relative fish population abundance, fishery catch and risk of population extinction. Our approach focuses solely on warming fresh waters as a key potential source of migration mortality, and does not consider other pathways of effects (e.g., forestry increases in fine sediment that decrease survival, decreased ocean survival). For more details, see Supporting Information.

4.2 | Scenario Results

Simulations across scenarios of climate change and riparian forest harvest reveal the SOS of a hypothetical sockeye salmon watershed (Figure 4A). Both local and global pressures combined to control sockeye salmon performance—combinations of higher global air temperatures and forestry harvest lead to a higher risk of compromised performance, indicated by depressed numbers of returning salmon (escapement), subsequent closure of the fishery, and then, if pressures keep increasing, extirpation. The degree of riparian forestry was a key control of salmon performance. At high levels of riparian forest harvest, the probability of fishery closure exceeded 50% by 2030 in nearly all climate scenarios. In contrast, salmon performance was maintained through 2100 across climate scenarios if riparian forests were fully protected or restored.

Thresholds in salmon performance emerged from the dual impacts of climate change and forestry on water temperatures (Figure 4C), which controlled adult salmon survival (Figure 4B). In general, under high emission scenarios and over longer time horizons, mean summer air temperatures increased, which increased stream temperatures. Specifically, mean summer air temperatures were predicted to increase in the simulation by 1°C–2°C by 2060 in all emissions scenarios except the lowest emissions scenario (SSP1-2.6). By 2080, air temperatures were predicted to increase by approximately 3°C–4°C under the high emissions scenarios (i.e., SSP3-7.0 and SSP5-8.5). However, riparian forest harvest strongly expedited the timing when simulated water temperatures exceeded 20°C, a temperature when salmon survival starts to decline. For example, in this specific formulation, when riparian area harvested was 15% or less, stream temperature exceeded 20°C in fewer than 5% of iterations for all years and climate emission scenarios. However, under the SSP3-7.0 scenario, stream temperatures started to exceed 20°C in nearly 25% of iterations by 2100 when 25% of riparian area is harvested and as early as 2025 when 35% of riparian area is harvested.

This simulation illustrates how salmon performance can be controlled by the combination of local pressure (e.g., riparian forestry) and global pressure (e.g., climate warming). The level of salmon performance response will vary depending on model formulation and parameters. Watersheds with warmer or cooler starting water temperatures would have smaller or larger SOS. In addition, this SOS simulation did not include other pressures, such as from declining ocean survival due to climate change or other forestry impacts, that would further contract the SOS. These features could be integrated into more process-based models, but were beyond the scope of this illustrative example.

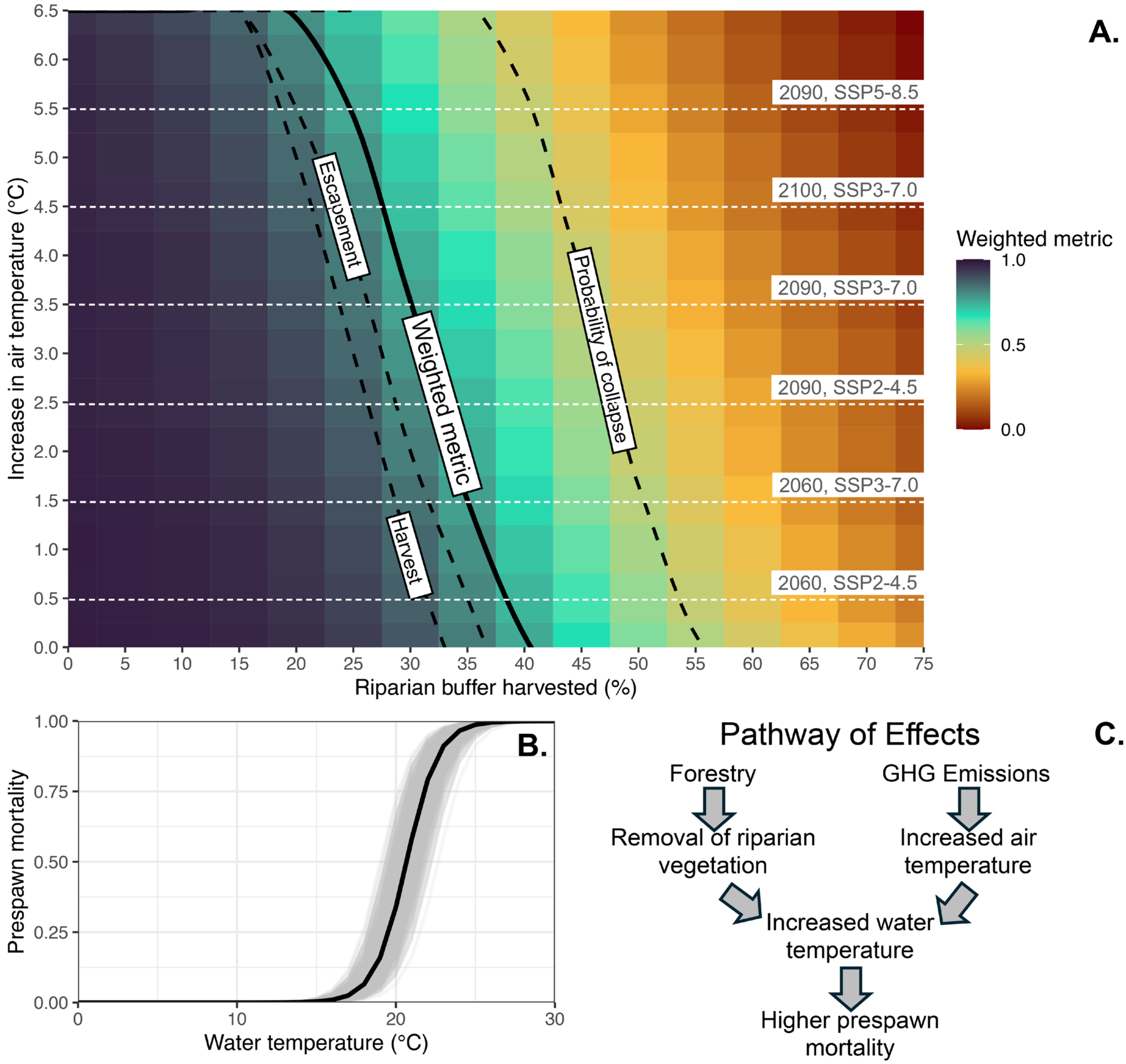

FIGURE 4 | (A) The safe operating space of a hypothetical sockeye salmon watershed, as explored with simulations across scenarios of climate change and riparian forest management. The SOS surface is defined by an integrative performance metric (solid line, colour of cells) that equally weighted escapement (the abundance of adult fish that make it to the spawning habitat), harvest and probability of extirpation (dashed lines). (B) Survival of simulated sockeye salmon followed a prespawn mortality stressor-response function. (C) The simulations explored a Climate Amplification Syndrome–how global emissions and local riparian forest harvest affect water temperature to harm salmon.

These scenarios are an example of how the SOS concept can be translated into analyses that function as decision-support tools to showcase management opportunities and trade-offs. To guide decision-making, models such as this should be tuned with local parameters and guided by the local community.

5 | Discussion

5.1 | Key Findings

Cumulative pressures from land use and climate change are pushing many salmon watersheds out of their natural range of variation to states of impoverishment (Murdoch et al. 2024; Ulaski et al. 2025; Ward et al. 2015; Warkentin et al. 2022; Wilson et al. 2022). We offer four syndromes of the combined impacts of climate change and local watershed activities that each present challenges and opportunities for management. For example, common extractive local land use industries, such as forestry and agriculture, share the same symptoms of climate change and thus will exacerbate oncoming climate risks. Alternatively, extractive local industries may damage or destroy future habitats and thus erode adaptive capacity. We illustrate how the SOS concept can be operationalised with collaborative decision-support tools that assess alternative plausible futures of salmon performance given local watershed land use, fisheries management and climate action. Collectively, this downscaling of the SOS concept to salmon watersheds showcases that local watershed management can either exacerbate or ameliorate oncoming climate risks to important aquatic ecosystems.

5.2 | Typologies of Safe Operating Spaces

SOS applications entail some understanding of the performance surface of the system, which could take a variety of typologies (Figure 5). SOS performance surfaces will vary across space and salmon species because different watershed characteristics and salmon adaptations will affect the underlying stressor–response functions (Jarvis et al. 2024; Rosenfeld et al. 2022), salmon population processes such as density dependence (Hodgson et al. 2017), and potential interactions among stressors. While meta-analyses suggest that additive impacts are more common than synergistic impacts (González-Espinosa et al. 2024), local and global pressures could have synergistic impacts where combinations of local and global stressors have greater than additive harms, resulting in a concave SOS boundary and a smaller SOS (Figure 5A). It is also possible that pressures could have antagonistic impacts, resulting in a convex boundary and larger SOS.

There is also likely strong variation in the degree to which different salmon watersheds are controlled by local versus global pressures (Figure 5B), likely differing across geographies, time and salmon life histories. If the performance surface of a salmon watershed is considered as a function of the feasible range of local and global climate pressures (Figure 5B), one option is that the performance surface is influenced similarly by both pressures, a 'balanced' typology. However, some systems may be primarily responsive to local processes rather than external forces, at least on a short time horizon ('local primacy', Figure 5B). For example, freshwater habitat and its degradation can limit production of stream-rearing coho salmon under some conditions (Bradford and Irvine 2000). Alternatively, salmon species with shorter freshwater phases, such as pink salmon, may be more likely to display 'climate-change primacy', where the SOS is more sensitive to global rather than local watershed pressures and there is little local agency for altering performance.

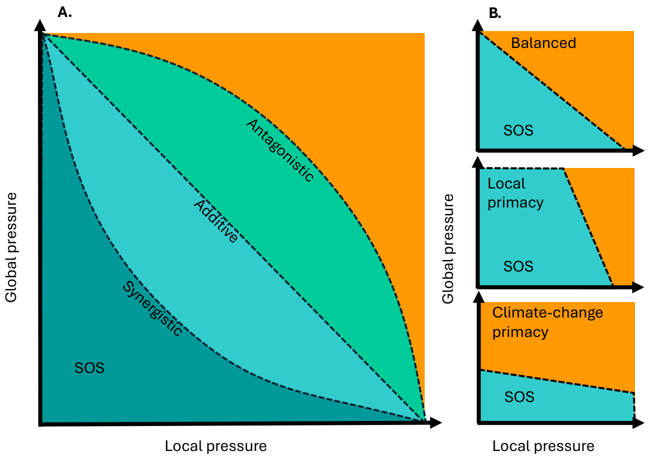

FIGURE 5 | Different typologies of SOS. (A) The performance surfaces of safe operating spaces and the corresponding boundaries of the safe space (dash lines) could be controlled by interactions between local and global pressures through antagonistic, additive, or synergistic interactions. (B) If SOS are plotted on similar axes that show the realm of possibility for local and global pressures, SOS surfaces could exhibit balanced, local primacy or climate-change primacy.

SOS with 'climate-change primacy' pose an obvious challenge for local managers—besides restricting fisheries, local managers have few obvious levers. However, even under climate-change primacy, salmon do rely on some level of watershed function that could be degraded by local pressures. While there is the temptation to invoke triage and give up on climate-change primacy systems that have been pushed to the boundaries of their SOS, we offer caution against this approach. First, studies that examine major climate symptoms like warm water temperatures often neglect to include land use as potential predictors and thus run the risk of falsely attributing all of the observed variance to climate and not local land use activities (e.g., (Moore 2006)). In addition, the watersheds that are the most stressed by climate may be the ones that contain the most important components of future adaptive capacity (e.g., genes for high thermal tolerance) (Eliason et al. 2011). Further, salmon populations can adapt their life-history timing and spatial distribution to avoid stressful climate conditions and thus may be more resilient than assumed (Reed et al. 2011). Climate-stressed systems can also be extremely productive under some seasons or climate conditions and thus may provide important contributions to the portfolio of salmon production over time (Armstrong et al. 2021). More generally, climate systems and salmon watersheds are inherently complex and unpredictable—there is a risk of being overly confident in predictive abilities (Schindler and Hilborn 2015). There are also important potential social reasons, such as other watershed benefits such as flood protection and human values other than salmon, to continue to invest in climate-primacy watersheds even if salmon populations are unlikely to recover. For these reasons, we caution against full triage and abandonment of climate-primacy watersheds.

5.3 | Management and Policy Options for Salmon Futures

There are a series of key management actions and policies that would increase the probability of keeping salmon watersheds in their SOS in the changing future.

5.3.1 | Climate Action for Salmon Futures

The pace and magnitude of climate change will be directly controlled by humanity's action (or inaction) to reduce greenhouse gas emissions. At more distant time horizons and high emissions scenarios, salmon will struggle as cool-water species in a warming world, regardless of local management. Targets for emissions reductions could be identified with SOS scenarios. While addressing global climate change is beyond the scope of local managers, the countries that support salmon in North America contribute disproportionately to global emissions–Canada and the USA are among the highest per-capita contributors of CO_2 emissions in the world (IPCC (Intergovernmental Panel on Climate Change) 2022). If salmon are culturally and societally important, they should be an additional motivator for local and global action on climate change.

5.3.2 | Managing the Shared Ocean

There are several key pressures on salmon systems at the ocean-basin scale, external to the control of local communities and managers, examples of the Migration Linkage Syndrome. Mixed-stock industrial salmon fisheries in the ocean may overharvest co-occurring weak or smaller stocks (Ricker 1958). Shifting the scale of some salmon fisheries from being external (e.g., industrial mixed-stock fisheries) to within salmon watersheds can both localise benefits and decrease mixed-stock overfishing challenges that are likely to escalate under climate change (Atlas et al. 2021; Moore et al. 2021). An additional major pressure at the ocean-basin scale is competition from mass-produced hatchery salmon, in particular pink salmon (Connors et al. 2024). Despite overwhelming evidence of international-level harm from pink salmon competition in the ocean, there remains little international oversight of hatchery releases (Holt et al. 2008). We flag these ocean-scale pressures as key contributors to the trajectories of salmon watersheds that need governance systems and policies.

5.3.3 | Landscape-Level Protections

Identification and protection of large intact watersheds or regions with functioning watersheds can support the maintenance and expression of resilience and adaptive capacity (Brennan et al. 2019; Healey 2009; Hilborn et al. 2003; Moore and Schindler 2022; Schindler et al. 2008, 2010). While we caution against "fortress conservation" that can displace local peoples and harm salmon-people relations, large-scale watershed protections could range from complete habitat protection to those that allow some low-level of industry activities in some regions (e.g., low level of forestry) but ban industrial-scale clear-cut logging and mega-projects such as major mines or oil and gas developments (Adams, Chauvenet, et al. 2023). Protections could be implemented via different visions or policies, such as 'Salmon Strongholds' (Rahr et al. 2025), 'Salmon Parks', or 'Indigenous Protected and Conserved Areas (IPCA)'. We also suggest that there are opportunities for landscape protections to be prioritised through forward-looking SOS scenarios, and thus consider oncoming climate-induced shifts in salmon habitat suitability (i.e., Adaptive Impairment Syndrome), such as emerging IPCAs that also protect emerging salmon habitats in glacierized areas (Moore et al. 2023).

5.3.4 | Reduction of Local Harms

Strengthened environmental regulations of local pressures will reduce local harms and thus increase the chances of keeping salmon watersheds in their SOS with climate change. Regulations of local industries may have already been insufficient or may not offer adequate protection of salmon watersheds given climate change if they were built on the climate-normal past. For example, strengthened regulations and extended protections of riparian habitats from agriculture, forestry and development would shade streams and help keep them cool despite climate warming (i.e., Climate Amplification Syndrome) (Cristea and Burges 2010; Fuller et al. 2022; Justice et al. 2017; Lawrence et al. 2014; Wondzell et al. 2019). Given the multitude of pressures encountered by salmon across their migratory life cycles (i.e., Independent Stressors Syndrome) (Chalifour et al. 2022; Ulaski et al. 2025), there is also a need for regulatory frameworks to address cumulative effects. Advancing best management practices for reducing harms as well as actions to restore key physical and ecosystem processes may also benefit salmon watersheds. While these actions may fail if they do not address root causes of problems (Bilby et al. 2024), process-based approaches such as restoring lateral and longitudinal connectivity can improve watershed climate resilience (Beechie, Imaki, et al. 2006).

5.3.5 | Create Road Maps and Paths to Watershed Sustainability

Different watershed states, pressures, trajectories and human values all present diverse management challenges and opportunities and call for various combinations of management and restoration approaches. There are a variety of available decision-support tools and approaches that could inform or guide forward-looking management of watersheds to keep them within their SOS, and these should be adopted by natural resource management agencies for regional cumulative effects assessments and development planning. For example, data-intensive life-cycle models with climate scenarios can identify different options for restoration or protection at local scales (Battin et al. 2007; Beechie, Imaki, et al. 2006). Decision analysis, including structured decision-making (Chalifour et al. 2022; Hemming et al. 2022), could use elicited and modelled values and co-developed management goals to inform the development of SOS models, outline different scenarios and thereby examine trade-offs associated with locally relevant management actions. These SOS applications should be robust to inherent variability of salmon watersheds, uncertainties of climate trajectories, non-stationarity of climate relationships and ecological surprises (Schindler and Hilborn 2015; Stier et al. 2022). As we consider paths to thriving watersheds for people and migratory fish, SOS applications offer opportunities to include alternative worldviews and values that are not built on the typical capitalist and colonial perspectives that prioritise short-term extraction of natural resources with some 'acceptable' level of environmental harm (Liboiron 2021; Pascual et al. 2023). While humanity has a massive footprint on Earth's watersheds, and there will inevitably be trade-offs in decision-making, the SOS framework may help upweight local values beyond watershed extraction to forward-looking watershed stewardship. Care needs to be taken that watershed plans set realistic expectations and centre local values to drive equitable and inclusive environmental decision-making and policy. There is also a key need for governance systems that can transform these SOS visions into policy actions, such as through responsive and local governance systems (Biggs et al. 2012; Connors 2023).

5.4 | Conclusions

Human-caused climate change is altering flow regimes, water temperatures and aquatic habitats, fundamentally shifting the foundation of past management approaches and policies (Milly et al. 2008). These climate pressures, in concert with harmful local watershed activities, profoundly harm freshwater biodiversity and the services they provide for humanity. Application of the SOS concept to salmon ecosystems reveals the power for local watershed management to exacerbate or ameliorate oncoming climate risks to important aquatic ecosystems. On the one hand, local human extractive activities erode the capacity of salmon ecosystems to cope with climate change and exacerbate climate risks. Alternatively, improving the local management of salmon ecosystems can provide large benefits to salmon resilience in this era of rapid climate change. This combination of information, local agency and hope is a key ingredient to positive socio-ecological transformations (Bennett et al. 2016). The core concepts advanced in this paper are simple yet have urgent and profound implications for the management of watersheds for migratory fish and people in a rapidly changing world. Integrative, inclusive and forward-looking watershed science that considers local pressures and climate impacts can inform, catalyse and inspire watershed stewardship actions and policies that enable positive trajectories of watersheds for fish and people.

Acknowledgements

This paper arose in part from conversations as part of the Watershed Futures Initiative at Simon Fraser University, an initiative supported by the British Columbia Restoration and Innovation Fund, Fisheries and Oceans Canada, the MakeWay Foundation, the Sitka Foundation, the Wilburforce Foundation, Natural Sciences and Engineering Research Council of Canada Discovery Grants to Jonathan W. Moore and Tara G. Martin, and Liber Ero Research Chairs to Jonathan W. Moore and Tara G. Martin. Two reviewers provided insightful and thoughtful feedback.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

References

Adams, M. S., V. J. D. Tulloch, J. Hemphill, et al. 2023. "Inclusive Approaches for Cumulative Effects Assessments." *People and Nature* 5, no. 2: 431–445. https://doi.org/10.1002/pan3.10447.

Adams, V. M., A. L. M. Chauvenet, N. Stoudmann, G. G. Gurney, D. Brockington, and C. D. Kuempel. 2023. "Multiple-Use Protected Areas Are Critical to Equitable and Effective Conservation." *One Earth* 6, no. 9: 1173–1189. https://doi.org/10.1016/j.oneear.2023.08.011.

Ainsworth, R. F., I. G. Cowx, and S. J. Funge-Smith. 2023. "Putting the Fish Into Inland Fisheries–A Global Allocation of Historic Inland Fish Catch." *Fish and Fisheries* 24, no. 2: 263–278. https://doi.org/10.1111/faf.12725.

Allan, J. D. 2004. "Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems." *Annual Review of Ecology, Evolution, and Systematics* 35, no. 1: 257–284. https://doi.org/10.1146/annurev.ecolsys.35.120202.110122.

Anderson, S. C., J. W. Moore, M. M. McClure, N. K. Dulvy, and A. B. Cooper. 2015. "Portfolio Conservation of Metapopulations Under Climate Change." *Ecological Applications* 25, no. 2: 559–572. https://doi.org/10.1890/14-0266.1.

Armstrong, J. B., A. H. Fullerton, C. E. Jordan, et al. 2021. "The Importance of Warm Habitat to the Growth Regime of Cold-Water Fishes." *Nature Climate Change* 11, no. 4: 354–361. https://doi.org/10.1038/s41558-021-00994-y.

Atlas, W. I., N. C. Ban, J. W. Moore, et al. 2021. "Indigenous Systems of Management for Culturally and Ecologically Resilient Pacific Salmon (*Oncorhynchus* spp.) Fisheries." *Bioscience* 71, no. 2: 186–204. https://doi.org/10.1093/biosci/biaa144.

Atlas, W. I., M. R. Sloat, W. H. Satterthwaite, et al. 2023. "Trends in Chinook Salmon Spawner Abundance and Total Run Size Highlight Linkages Between Life History, Geography and Decline." *Fish and Fisheries* 24, no. 4: 595–617. https://doi.org/10.1111/faf.12750.

Battin, J., M. W. Wiley, M. H. Ruckelshaus, et al. 2007. "Projected Impacts of Climate Change on Salmon Habitat Restoration." *Proceedings of the National Academy of Sciences* 104, no. 16: 6720–6725. https://doi.org/10.1073/pnas.0701685104.

Beechie, T., E. Buhle, M. Ruckelshaus, A. Fullerton, and L. Holsinger. 2006. "Hydrologic Regime and the Conservation of Salmon Life History Diversity." *Biological Conservation* 130, no. 4: 560–572. https://doi.org/10.1016/j.biocon.2006.01.019.

Beechie, T., H. Imaki, J. Greene, et al. 2006. "Restoring Salmon Habitat for a Changing Climate." *River Research and Applications* 29, no. 8: 939–960. https://doi.org/10.1002/rra.2590.

Bennett, E. M., M. Solan, R. Biggs, et al. 2016. "Bright Spots: Seeds of a Good Anthropocene." *Frontiers in Ecology and the Environment* 14, no. 8: 441–448. https://doi.org/10.1002/fee.1309.

Biggs, R., M. Schlüter, D. Biggs, et al. 2012. "Toward Principles for Enhancing the Resilience of Ecosystem Services." *Annual Review of Environment and Resources* 37, no. 1: 421–448. https://doi.org/10.1146/annurev-environ-051211-123836.

Bilby, R. E., K. P. Currens, K. L. Fresh, D. B. Booth, R. R. Fuerstenberg, and G. L. Lucchetti. 2024. "Why Aren't Salmon Responding to Habitat Restoration in the Pacific Northwest?" *Fisheries* 49, no. 1: 16–27. https://doi.org/10.1002/fsh.10991.

Bisson, P. A., J. B. Dunham, and G. H. Reeves. 2009. "Freshwater Ecosystems and Resilience of Pacific Salmon: Habitat Management Based on Natural Variability." *Ecology and Society* 14, no. 1: art45. https://doi.org/10.5751/ES-02784-140145.

Bottom, D. L., K. K. Jones, T. J. Cornwell, A. Gray, and C. A. Simenstad. 2005. "Patterns of Chinook Salmon Migration and Residency in the Salmon River Estuary (Oregon)." *Estuarine, Coastal and Shelf Science* 64, no. 1: 79–93. https://doi.org/10.1016/j.ecss.2005.02.008.

Bradford, M. J., and J. R. Irvine. 2000. "Land Use, Fishing, Climate Change, and the Decline of Thompson River, British Columbia, Coho Salmon." *Canadian Journal of Fisheries and Aquatic Sciences* 57, no. 1: 13–16.

Brennan, S. R., D. E. Schindler, T. J. Cline, T. E. Walsworth, G. Buck, and D. P. Fernandez. 2019. "Shifting Habitat Mosaics and Fish Production Across River Basins." *Science* 364, no. 6442: 783–786. https://doi.org/10.1126/science.aav4313.

Carlson, S. M., A. Ruhi, M. T. Bogan, et al. 2023. "Losing Flow in Free-Flowing Mediterranean-Climate Streams." *Frontiers in Ecology and the Environment* 22: e2737.

Carlson, S. M., and W. H. Satterthwaite. 2011. "Weakened Portfolio Effect in a Collapsed Salmon Population Complex." *Canadian Journal of Fisheries and Aquatic Sciences* 68, no. 9: 1579–1589. https://doi.org/10.1139/f2011-084.

Carothers, C., J. Black, S. J. Langdon, et al. 2021. "Indigenous Peoples and Salmon Stewardship: A Critical Relationship." *Ecology and Society* 26, no. 1: art16. https://doi.org/10.5751/ES-11972-260116.

Carpenter, S. R., W. A. Brock, G. J. A. Hansen, et al. 2017. "Defining a Safe Operating Space for Inland Recreational Fisheries." *Fish and Fisheries* 18, no. 6: 1150–1160. https://doi.org/10.1111/faf.12230.

Chalifour, L., C. Holt, A. E. Camaclang, et al. 2022. "Identifying a Pathway Towards Recovery for Depleted Wild Pacific Salmon Populations in a Large Watershed Under Multiple Stressors." *Journal* *of Applied Ecology* 59, no. 9: 2212–2226. https://doi.org/10.1111/1365-2664.14239.

Connors, B., G. T. Ruggerone, and J. R. Irvine. 2024. "Adapting Management of Pacific Salmon to a Warming and More Crowded Ocean." *ICES Journal of Marine Science* 82: fsae135. https://doi.org/10.1093/icesjms/fsae135.

Connors, K. 2023. "Mismatches in Salmon Social–Ecological Systems: Challenges and Opportunities for (Re)alignment in the Skeena River Watershed." *Facets* 8: 1–30. https://doi.org/10.1139/facets-2022-0028.

Cristea, N. C., and S. J. Burges. 2010. "An Assessment of the Current and Future Thermal Regimes of Three Streams Located in the Wenatchee River Basin, Washington State: Some Implications for Regional River Basin Systems." *Climatic Change* 102, no. 3-4: 493–520. https://doi.org/10.1007/s10584-009-9700-5.

Crozier, L. G., and J. E. Siegel. 2023. "A Comprehensive Review of the Impacts of Climate Change on Salmon: Strengths and Weaknesses of the Literature by Life Stage." *Fishes* 8, no. 6: 319.

Cunningham, C. J., P. A. H. Westley, and M. D. Adkison. 2018. "Signals of Large Scale Climate Drivers, Hatchery Enhancement, and Marine Factors in Yukon River Chinook Salmon Survival Revealed With a Bayesian Life History Model." *Global Change Biology* 24, no. 9: 4399–4416. https://doi.org/10.1111/gcb.14315.

Cunningham, D. S., D. C. Braun, J. W. Moore, and A. M. Martens. 2023. "Forestry Influences on Salmonid Habitat in the North Thompson River Watershed, British Columbia." *Canadian Journal of Fisheries and Aquatic Sciences* 80, no. 7: 1053–1070. https://doi.org/10.1139/cjfas-2022-0255.

Davis, M. J., I. Woo, C. S. Ellings, et al. 2022. "A Climate-Mediated Shift in the Estuarine Habitat Mosaic Limits Prey Availability and Reduces Nursery Quality for Juvenile Salmon." *Estuaries and Coasts* 45, no. 5: 1445–1464. https://doi.org/10.1007/s12237-021-01003-3.

Donkersloot, R., J. C. Black, C. Carothers, et al. 2020. "Assessing the Sustainability and Equity of Alaska Salmon Fisheries Through a Well-Being Framework." *Ecology and Society* 25, no. 2: art18. https://doi.org/10.5751/ES-11549-250218.

Dunmall, K., J. A. Langan, C. J. Cunningham, J. D. Reist, and H. Melling. 2024. "Pacific Salmon in the Canadian Arctic Highlight a Range-Expansion Pathway for Salmon." *Global Change Biology* 30: e17353.

Ebersole, J. L., R. M. Quiñones, S. Clements, and B. H. Letcher. 2020. "Managing Climate Refugia for Freshwater Fishes Under an Expanding Human Footprint." *Frontiers in Ecology and the Environment* 18, no. 5: 271–280. https://doi.org/10.1002/fee.2206.

Eliason, E. J., T. D. Clark, M. J. Hague, et al. 2011. "Differences in Thermal Tolerance Among Sockeye Salmon Populations." *Science* 332, no. 6025: 109–112. https://doi.org/10.1126/science.1199158.

Falkenmark, M., L. Wang-Erlandsson, and J. Rockström. 2019. "Understanding of Water Resilience in the Anthropocene." *Journal of Hydrology X* 2: 100009. https://doi.org/10.1016/j.hydroa.2018.100009.

Finn, R. J. R., M. Ned-Kwilosintun, L. Ballantyne, et al. 2024. "Reclaiming the Xhotsa: Climate Adaptation and Ecosystem Restoration via the Return of Sumas Lake." *Frontiers in Conservation Science* 5: 1380083. https://doi.org/10.3389/fcosc.2024.1380083.

FitzGerald, A. M., S. N. John, T. M. Apgar, N. J. Mantua, and B. T. Martin. 2021. "Quantifying Thermal Exposure for Migratory Riverine Species: Phenology of Chinook Salmon Populations Predicts Thermal Stress." *Global Change Biology* 27, no. 3: 536–549. https://doi.org/10.1111/gcb.15450.

Flitcroft, R., K. Burnett, and K. Christiansen. 2013. "A Simple Model That Identifies Potential Effects of Sea-Level Rise on Estuarine and Estuary-Ecotone Habitat Locations for Salmonids in Oregon, USA." *Environmental Management* 52, no. 1: 196–208. https://doi.org/10.1007/s00267-013-0074-0.

Ford, J., and G. Ellis. 2006. "Selective Foraging by Fish-Eating Killer Whales *Orcinus orca* in British Columbia." *Marine Ecology Progress Series* 316: 185–199. https://doi.org/10.3354/meps316185.

Fuller, M. R., N. E. Detenbeck, P. Leinenbach, R. Labiosa, and D. Isaak. 2024. "Scenario Planning Management Actions to Restore Cold Water Stream Habitat: Comparing Mechanistic and Statistical Modeling Approaches." *River Research and Applications* 41: rra.4381. https://doi.org/10.1002/rra.4381.

Fuller, M. R., P. Leinenbach, N. E. Detenbeck, R. Labiosa, and D. J. Isaak. 2022. "Riparian Vegetation Shade Restoration and Loss Effects on Recent and Future Stream Temperatures." *Restoration Ecology* 30, no. 7: e13626. https://doi.org/10.1111/rec.13626.

Garibaldi, A., and N. Turner. 2004. "Cultural Keystone Species: Implications for Ecological Conservation and Restoration." *Ecology and Society* 9, no. 3: art1. https://doi.org/10.5751/ES-00669-090301.

González-Espinosa, P. C., L. Jarvis, S. Cannon, et al. 2024. "Quantifying the Interactions and Cumulative Effects of Multiple Stressors on Salmonids." *Environmental Management*: 1–13. https://doi.org/10.1007/s00267-024-02102-0.

Green, A. J., P. Alcorlo, E. T. Peeters, et al. 2017. "Creating a Safe Operating Space for Wetlands in a Changing Climate." *Frontiers in Ecology and the Environment* 15, no. 2: 99–107. https://doi.org/10.1002/fee.1459.

Griffiths, J. R., D. E. Schindler, J. B. Armstrong, et al. 2014. "Performance of Salmon Fishery Portfolios Across Western North America." *Journal of Applied Ecology* 51, no. 6: 1554–1563. https://doi.org/10.1111/1365-2664.12341.

Gronsdahl, S., R. D. Moore, J. Rosenfeld, R. McCleary, and R. Winkler. 2019. "Effects of Forestry on Summertime Low Flows and Physical Fish Habitat in Snowmelt-Dominant Headwater Catchments of the Pacific Northwest." *Hydrological Processes* 33, no. 25: 3152–3168. https://doi.org/10.1002/hyp.13580.

Gustafson, R. G., R. S. Waples, J. M. Myers, et al. 2007. "Pacific Salmon Extinctions: Quantifying Lost and Remaining Diversity." *Conservation Biology* 21, no. 4: 1009–1020. https://doi.org/10.1111/j.1523-1739.2007.00693.x.

Hansen, G. J. A., L. A. Winslow, J. S. Read, M. Treml, P. J. Schmalz, and S. R. Carpenter. 2019. "Water Clarity and Temperature Effects on Walleye Safe Harvest: An Empirical Test of the Safe Operating Space Concept." *Ecosphere* 10, no. 5: e02737. https://doi.org/10.1002/ecs2.2737.

Healey, M. C. 2009. "Resilient Salmon, Resilient Fisheries for British Columbia, Canada." *Ecology and Society* 14, no. 1: art2. https://doi.org/10.5751/ES-02619-140102.

Hemming, V., A. E. Camaclang, M. S. Adams, et al. 2022. "An Introduction to Decision Science for Conservation." *Conservation Biology* 36, no. 1: e13868. https://doi.org/10.1111/cobi.13868.

Hilborn, R., T. P. Quinn, D. E. Schindler, and D. E. Rogers. 2003. "Biocomplexity and Fisheries Sustainability." *Proceedings of the National Academy of Sciences* 100, no. 11: 6564–6568. https://doi.org/10.1073/pnas.1037274100.

Hodgson, E. E., T. E. Essington, and B. S. Halpern. 2017. "Density Dependence Governs When Population Responses to Multiple Stressors Are Magnified or Mitigated." *Ecology* 98, no. 10: 2673–2683. https://doi.org/10.1002/ecy.1961.

Holt, C. A., M. B. Rutherford, and R. M. Peterman. 2008. "International Cooperation Among Nation-States of the North Pacific Ocean on the Problem of Competition Among Salmon for a Common Pool of Prey Resources." *Marine Policy* 32, no. 4: 607–617. https://doi.org/10.1016/j.marpol.2007.11.001.

Iacarella, J. C., and J. D. Weller. 2024. "Predicting Favourable Streams for Anadromous Salmon Spawning and Natal Rearing Under Climate

Change." *Canadian Journal of Fisheries and Aquatic Sciences* 81, no. 1: 1–13. https://doi.org/10.1139/cjfas-2023-0096.

IPCC (Intergovernmental Panel on Climate Change). 2022. "Climate Change 2022: Impacts, Adaptation, and Vulnerability. IPCC Sixth Assessment Report."

Jarvis, L., J. Rosenfeld, P. C. Gonzalez-Espinosa, and E. C. Enders. 2024. "A Process Framework for Integrating Stressor-Response Functions Into Cumulative Effects Models." *Science of the Total Environment* 906: 167456. https://doi.org/10.1016/j.scitotenv.2023.167456.

Johnson, C. J. 2013. "Identifying Ecological Thresholds for Regulating Human Activity: Effective Conservation or Wishful Thinking?" *Biological Conservation* 168: 57–65. https://doi.org/10.1016/j.biocon.2013.09.012.

Justice, C., S. M. White, D. A. McCullough, D. S. Graves, and M. R. Blanchard. 2017. "Can Stream and Riparian Restoration Offset Climate Change Impacts to Salmon Populations?" *Journal of Environmental Management* 188: 212–227. https://doi.org/10.1016/j.jenvman.2016.12.005.

Lamb, C. T., R. Willson, A. K. Menzies, et al. 2023. "Braiding Indigenous Rights and Endangered Species Law." *Science* 380, no. 6646: 694–696. https://doi.org/10.1126/science.adg9830.

Langan, J. A., C. J. Cunningham, J. T. Watson, and S. McKinnell. 2024. "Opening the Black Box: New Insights Into the Role of Temperature in the Marine Distributions of Pacific Salmon." *Fish and Fisheries* 25, no. 4: 551–568. https://doi.org/10.1111/faf.12825.

Lawrence, D. J., B. Stewart-Koster, J. D. Olden, et al. 2014. "The Interactive Effects of Climate Change, Riparian Management, and a Nonnative Predator on Stream-Rearing Salmon." *Ecological Applications* 24, no. 4: 895–912. https://doi.org/10.1890/13-0753.1.

Leach, J. A., C. Kelleher, B. L. Kurylyk, R. D. Moore, and B. T. Neilson. 2023. "A Primer on Stream Temperature Processes." *WIREs Water* 10, no. 4: e1643. https://doi.org/10.1002/wat2.1643.

Levi, T., C. T. Darimont, M. MacDuffee, M. Mangel, P. Paquet, and C. C. Wilmers. 2012. "Using Grizzly Bears to Assess Harvest-Ecosystem Tradeoffs in Salmon Fisheries." *PLoS Biology* 10, no. 4: e1001303. https://doi.org/10.1371/journal.pbio.1001303.

Liboiron, M. 2021. *Pollution Is Colonialism*. Duke University Press.

Mahony, C. R., T. Wang, A. Hamann, and A. J. Cannon. 2022. "A Global Climate Model Ensemble for Downscaled Monthly Climate Normals Over North America." *International Journal of Climatology* 42, no. 11: 5871–5891. https://doi.org/10.1002/joc.7566.

Mantua, N., I. Tohver, and A. Hamlet. 2010. "Climate Change Impacts on Streamflow Extremes and Summertime Stream Temperature and Their Possible Consequences for Freshwater Salmon Habitat in Washington State." *Climatic Change* 102, no. 1-2: 187–223. https://doi.org/10.1007/s10584-010-9845-2.

Martin, T. G., M. A. Burgman, F. Fidler, et al. 2012. "Eliciting Expert Knowledge in Conservation Science." *Conservation Biology* 26, no. 1: 29–38. https://doi.org/10.1111/j.1523-1739.2011.01806.x.

Milly, P. C. D., J. Betancourt, M. Falkenmark, et al. 2008. "Stationarity Is Dead: Whither Water Management?" *Science* 319, no. 5863: 573–574. https://doi.org/10.1126/science.1151915.

Montgomery, D. R. 1999. "Process Domains and the River Continuum." *JAWRA Journal of the American Water Resources Association* 35, no. 2: 397–410. https://doi.org/10.1111/j.1752-1688.1999.tb03598.x.

Moore, J. W., B. M. Connors, and E. E. Hodgson. 2021. "Conservation Risks and Portfolio Effects in Mixed-Stock Fisheries." *Fish and Fisheries* 22: 1024–1040.

Moore, J. W., M. McClure, L. A. Rogers, and D. E. Schindler. 2010. "Synchronization and Portfolio Performance of Threatened Salmon." *Conservation Letters* 3, no. 5: 340–348. https://doi.org/10.1111/j.1755-263X.2010.00119.x.

Moore, J. W., K. J. Pitman, D. Whited, et al. 2023. "Mining Stakes Claim on Salmon Futures as Glaciers Retreat." *Science* 382, no. 6673: 887–889. https://doi.org/10.1126/science.adj4911.

Moore, J. W., and D. E. Schindler. 2022. "Getting Ahead of Climate Change for Ecological Adaptation and Resilience." *Science* 376, no. 6600: 1421–1426. https://doi.org/10.1126/science.abo3608.

Moore, R. D. 2006. "Stream Temperature Patterns in British Columbia, Canada, Based on Routine Spot Measurements." *Canadian Water Resources Journal* 31, no. 1: 41–56. https://doi.org/10.4296/cwrj3101041.

Moore, R. D., and J. S. Richardson. 2012. "Natural Disturbance and Forest Management in Riparian Zones: Comparison of Effects at Reach, Catchment, and Landscape Scales." *Freshwater Science* 31, no. 1: 239–247. https://doi.org/10.1899/11-030.1.

Mu, H., X. Li, Y. Wen, et al. 2022. "A Global Record of Annual Terrestrial Human Footprint Dataset From 2000 to 2018." *Scientific Data* 9, no. 1: 176. https://doi.org/10.1038/s41597-022-01284-8.

Munsch, S., C. M. Greene, N. J. Mantua, and W. H. Satterthwaite. 2022. "One Hundred-Seventy Years of Stressors Erode Salmon Fishery Climate Resilience in California's Warming Landscape." *Global Change Biology* 28: 2183–2201.

Murdoch, A., B. M. Connors, N. W. R. Lapointe, J. Mills Flemming, S. J. Cooke, and C. Mantyka-Pringle. 2024. "Multiple Environmental Drivers Across Life Stages Influence Yukon River Chinook Salmon Productivity." *Canadian Journal of Fisheries and Aquatic Sciences* 81, no. 1: 97–114. https://doi.org/10.1139/cjfas-2022-0254.

Naish, K. A., J. E. Taylor, P. S. Levin, et al. 2007. "An Evaluation of the Effects of Conservation and Fishery Enhancement Hatcheries on Wild Populations of Salmon." In *Advances in Marine Biology*, vol. 53, 61–194. Elsevier. https://doi.org/10.1016/S0065-2881(07)53002-6.

Naman, S. M., K. J. Pitman, D. S. Cunningham, et al. 2024. "Forestry Impacts on Stream Flows and Temperatures: A Quantitative Synthesis of Paired Catchment Studies Across the Pacific Salmon Range." *Ecological Solutions and Evidence* 5, no. 2: e12328. https://doi.org/10.1002/2688-8319.12328.

Nehlsen, W., J. E. Williams, and J. A. Lichatowich. 1991. "Pacific Salmon at the Crossroads: Stocks at Risk From California, Oregon, Idaho, and Washington." *Fisheries* 16, no. 2: 4–21.

Nesbitt, H. K., and J. W. Moore. 2016. "Species and Population Diversity in Pacific Salmon Fisheries Underpin Indigenous Food Security." *Journal of Applied Ecology* 53, no. 5: 1489–1499. https://doi.org/10.1111/1365-2664.12717.

Pascual, U., P. Balvanera, C. B. Anderson, et al. 2023. "Diverse Values of Nature for Sustainability." *Nature* 620, no. 7975: 813–823. https://doi.org/10.1038/s41586-023-06406-9.

Pess, G. R., M. L. McHenry, K. Denton, et al. 2024. "Initial Responses of Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead (*Oncorhynchus mykiss*) to Removal of Two Dams on the Elwha River, Washington State, USA." *Frontiers in Ecology and Evolution* 12: 1241028. https://doi.org/10.3389/fevo.2024.1241028.

Peterson, W. T., J. L. Fisher, P. T. Strub, et al. 2017. "The Pelagic Ecosystem in the Northern California Current Off Oregon During the 2014–2016 Warm Anomalies Within the Context of the Past 20 Years." *Journal of Geophysical Research: Oceans* 122, no. 9: 7267–7290. https://doi.org/10.1002/2017JC012952.

Pitman, K. J., J. W. Moore, M. Huss, et al. 2021. "Glacier Retreat Creating New Pacific Salmon Habitat in Western North America." *Nature Communications* 12, no. 1: 6816. https://doi.org/10.1038/s41467-021-26897-2.

Pitman, K. J., J. W. Moore, M. R. Sloat, et al. 2020. "Glacier Retreat and Pacific Salmon." *Bioscience* 70, no. 3: 220–236. https://doi.org/10.1093/biosci/biaa015.

Rahr, G. R., M. R. Sloat, W. I. Atlas, and J. L. Hart. 2025. "Strongholds for Pacific Salmon: A Proactive Conservation Strategy for Ecosystem Health, Food Security, Biodiversity, and Climate Resilience." *Fisheries*: vuaf011. https://doi.org/10.1093/fshmag/vuaf011.

Raworth, K. 2017. "A Doughnut for the Anthropocene: Humanity's Compass in the 21st Century." *Lancet Planetary Health* 1, no. 2: e48–e49. https://doi.org/10.1016/S2542-5196(17)30028-1.

Reed, T. E., D. E. Schindler, M. J. Hague, et al. 2011. "Time to Evolve? Potential Evolutionary Responses of Fraser River Sockeye Salmon to Climate Change and Effects on Persistence." *PLoS One* 6, no. 6: e20380. https://doi.org/10.1371/journal.pone.0020380.

Reid, A. J., A. K. Carlson, I. F. Creed, et al. 2019. "Emerging Threats and Persistent Conservation Challenges for Freshwater Biodiversity." *Biological Reviews* 94, no. 3: 849–873. https://doi.org/10.1111/brv.12480.

Reid, A. J., N. Young, S. G. Hinch, and S. J. Cooke. 2022. "Learning From Indigenous Knowledge Holders on the State and Future of Wild Pacific Salmon." *Facets* 7: 718–740. https://doi.org/10.1139/facets-2021-0089.

Ricker, W. E. 1958. "Maximum Sustained Yields From Fluctuating Environments and Mixed Stocks." *Journal of the Fisheries Research Board of Canada* 15, no. 5: 991–1006. https://doi.org/10.1139/f58-054.

Rockström, J., and L. Karlberg. 2010. "The Quadruple Squeeze: Defining the Safe Operating Space for Freshwater Use to Achieve a Triply Green Revolution in the Anthropocene." *Ambio* 39, no. 3: 257–265. https://doi.org/10.1007/s13280-010-0033-4.

Rockström, J., W. Steffen, K. Noone, et al. 2009. "Planetary Boundaries: Exploring the Safe Operating Space for Humanity." *Ecology and Society* 14, no. 2: art32. https://doi.org/10.5751/ES-03180-140232.

Rosenfeld, J., P. Gonzalez-Espinosa, L. Jarvis, et al. 2022. "Stressor-Response Functions as a Generalizable Model for Context Dependence." *Trends in Ecology & Evolution* 37, no. 12: 1032–1035. https://doi.org/10.1016/j.tree.2022.09.010.

Sayer, C. A., E. Fernando, R. R. Jimenez, et al. 2025. "One-Quarter of Freshwater Fauna Threatened With Extinction." *Nature* 638: 138–145. https://doi.org/10.1038/s41586-024-08375-z.

Scheffer, M., S. Barrett, S. R. Carpenter, et al. 2015. "Creating a Safe Operating Space for Iconic Ecosystems." *Science* 347, no. 6228: 1317–1319. https://doi.org/10.1126/science.aaa3769.

Schindler, D. E., X. Augerot, E. Fleishman, et al. 2008. "Climate Change, Ecosystem Impacts, and Management for Pacific Salmon." *Fisheries* 33, no. 10: 502–506. https://doi.org/10.1577/1548-8446-33.10.502.

Schindler, D. E., and R. Hilborn. 2015. "Prediction, Precaution, and Policy Under Global Change." *Science* 347, no. 6225: 953–954. https://doi.org/10.1126/science.1261824.

Schindler, D. E., R. Hilborn, B. Chasco, et al. 2010. "Population Diversity and the Portfolio Effect in an Exploited Species." *Nature* 465, no. 7298: 609–612. https://doi.org/10.1038/nature09060.

Sergeant, C. J., E. K. Sexton, J. W. Moore, et al. 2022. "Risks of Mining to Salmonid-Bearing Watersheds." *Science Advances* 8, no. 26: eabn0929. https://doi.org/10.1126/sciadv.abn0929.

Sloat, M. R., G. H. Reeves, and K. R. Christiansen. 2017. "Stream Network Geomorphology Mediates Predicted Vulnerability of Anadromous Fish Habitat to Hydrologic Change in Southeast Alaska." *Global Change Biology* 23, no. 2: 604–620. https://doi.org/10.1111/gcb.13466.

Stanford, J. A., M. S. Lorang, and F. R. Hauer. 2005. "The Shifting Habitat Mosaic of River Ecosystems." *SIL Proceedings, 1922–2010* 29, no. 1: 123–136. https://doi.org/10.1080/03680770.2005.11901979.

Stier, A. C., T. E. Essington, J. F. Samhouri, et al. 2022. "Avoiding Critical Thresholds Through Effective Monitoring." *Proceedings of the Royal Society B: Biological Sciences* 289: 20220526. https://doi.org/10.1098/rspb.2022.0526.

Ulaski, M. E., J. W. Moore, D. Carlson, et al. 2025. "Barriers and Opportunities for the Effective Management of Cumulative Effects in Salmon Ecosystems in British Columbia, Canada." *FACETS* 10: 1–25.

Ward, E. J., J. H. Anderson, T. J. Beechie, G. R. Pess, and M. J. Ford. 2015. "Increasing Hydrologic Variability Threatens Depleted Anadromous Fish Populations." *Global Change Biology* 21, no. 7: 2500–2509. https://doi.org/10.1111/gcb.12847.

Warkentin, L., C. K. Parken, R. Bailey, and J. W. Moore. 2022. "Low Summer River Flows Associated With Low Productivity of Chinook Salmon in a Watershed With Shifting Hydrology." *Ecological Solutions and Evidence* 3, no. 1: e12124. https://doi.org/10.1002/2688-8319.12124.

Wilson, K. L., C. J. Bailey, T. D. Davies, and J. W. Moore. 2022. "Marine and Freshwater Regime Changes Impact a Community of Migratory Pacific Salmonids in Decline." *Global Change Biology* 28, no. 1: 72–85. https://doi.org/10.1111/gcb.15895.

Wondzell, S. M., M. Diabat, and R. Haggerty. 2019. "What Matters Most: Are Future Stream Temperatures More Sensitive to Changing Air Temperatures, Discharge, or Riparian Vegetation?" *JAWRA Journal of the American Water Resources Association* 55, no. 1: 116–132. https://doi.org/10.1111/1752-1688.12707.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** faf70027-sup-0001-DataS1.docx.