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Barriers and opportunities for the effective management of cumulative effects in salmon ecosystems in British Columbia, Canada

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Abstract

The cumulative effects of climate change and human activities pose major challenges for environmental management, a problem exemplified by Pacific salmon ecosystems. We offer an integrative treatment of both the science and policy levers of cumulative effects and reveal the sheer complexity of effective governance of salmon ecosystems in British Columbia, Canada. We then present and examine a hypothetical conceptualization of cumulative effects and their governance in salmon ecosystems to highlight several barriers and opportunities. We find that the progressive degradation of many salmon habitats appears to be enabled by the current policy approach through scarce monitoring, ineffective assessment, lack of legal limits, and isolated decision-making. At the same time, climate change magnifies the urgency of effective management as human activities act cumulatively with climate change impacts. However, our synthesis also highlights opportunities with existing but underused policy levers within Crown and Indigenous governance, as well as local co-governance arrangements, that could improve salmon ecosystem management. Although positive steps have been made toward managing several stressors, the current challenges facing Pacific salmon underscore the need for a fundamental shift in the treatment of cumulative effects.

Key words: cumulative effects, governance, law, policy, Pacific salmon, multiple stressors

Introduction

Multiple human activities cause cumulative harm to social-ecological systems around the world and pose a series of challenges for both science and management (Steffen et al. 2011). First, the cumulative impact of small incremental changes or stressors (Table 1) over time can lead to significant negative outcomes or "death by a thousand cuts" (Laurance 2010; Cohen 2012). Second, the effects of human activities on ecosystems are often complex and difficult to predict, especially when systems differ in their sensitivity to stressors due to their diverse environmental or ecological traits (Chezik et al. 2015; Lisi et al. 2015). Third, the impacts of activities can take years, decades, or even centuries to fully manifest or may be remote from the activity's origin, impeding the rapid identification and mediation of effects (Downs and Piégay 2019). Fourth, impacts may accumulate from human activities from multiple jurisdictions within and between governments, which can create barriers to managing these effects (Scarlett and McKinney 2016).

Effectively addressing cumulative effects requires overcoming scientific challenges in detecting and predicting them, as well as policy shortcomings in managing these impacts equitably and inclusively. Regulatory frameworks for managing cumulative effects are often inadequate because they tend to require consideration of only the isolated effects of individual projects or activities rather than the cumulative impact of all activities over time (Parkes et al. 2016; Adams et al. 2023). Cumulative effects policies may also struggle to have inclusive processes that effectively incorporate plural and potentially conflicting values among stakeholders and

Table 1. Definitions of key terms.

Term	Definition
Baseline	An observation or value that represents the normal or beginning level of a system.
Benchmark	A standard or point of reference against which conditions can be compared, which are defined by a set of values.
Crown governments	In Canada, Crown governments refer to the federal, provincial, and territorial governments, with municipalities operating under authority delegated by provinces or territories.
Cumulative effects	Changes to an ecosystem due to the combined effects of past, present, and future human activities and natural processes.
Cumulative effects assessment (CEA)	Most known as a component of Environmental Assessment that identifies, evaluates, and reduces the effects of multiple activities on the environment. Cumulative effects assessment can also refer to other assessment processes outside of regulatory Environmental Assessment that detect or predict the effects of multiple activities.
Cumulative effects management cycle	A feedback loop connecting the pathways of impacts on ecosystems, assessment of the state of the ecosystem, and governance.
Stressor-based assessment	A component of cumulative effects assessment where stressors associated with development activities are identified and their effects on ecosystem components are predicted based on known pathways of effects (Dubé et al. 2013).
Accumulated state assessment	A component of cumulative effects assessment that measures accumulated change in key ecosystem indicators over space and time relative to a reference state (Dubé et al. 2013).
Pathway of effects	Chain of causal linkages from human activities to stressors, to ecosystem processes and conditions, to a biological response.
Regional assessment	Most known as a component of Environmental Assessment that evaluates cumulative effects of multiple activities over large areas, providing a broader environmental context for development. Regional assessment can also refer to other assessment processes outside of regulatory Environmental Assessment.
Stressor	Any environmental variable that can directly or indirectly cause a biological response.

Note: The definitions below are not meant to be comprehensive as these terms often have multiple meanings but serve as working definitions used in this paper.

rightsholders (Brush 2020; Pascual et al. 2023). In particular, political and economic pressure from industry on colonial governments and environmental regulators can result in disproportionate harm to the environment and Indigenous Peoples, such as the loss of traditional livelihoods (St-Laurent and Le Billon 2015; Muir 2022). Legal systems may uphold unjust social, economic, and political power structures and thus contribute to driving cumulative effects of human activities. Thus, if healthy and just futures for important ecosystems and people are a priority, there is an urgent need to understand how to more effectively and equitably regulate human activities that cause cumulative effects in ecosystems.

Salmon ecosystems are an essential part of the economic, cultural, and ecological tapestry of coastal North America, but they have been transformed since European contact. For over 10 000 years, human–salmon relationships have formed a foundation of complex social-ecological systems with sophisticated stewardship, laws, and deep connections between humans and ecosystems (Salmón 2000; Campbell and Butler 2010; Atlas et al. 2021). The persistence of human–salmon relationships over millennia, despite major climatic changes and disturbances (Waples et al. 2009), demonstrates the resilience of these social-ecological systems and the sustainable stewardship by Indigenous Peoples (Campbell and Butler 2010). However, Indigenous stewardship practices have been actively suppressed since the onset of European colonization (Truth and Reconciliation Commission 2015), and extractive and capitalistic practices have been prioritized in the management of Pacific salmon and ecosystems (Harris 2001; Atlas et al. 2021).

Pacific salmon are exposed to an increasingly complex landscape of interacting stressors (Toft et al. 2017; Hodgson et al. 2020; Tulloch et al. 2022). Stressors from human activities such as fishing, forestry, mining, agriculture, urban development, hydroelectric development, and salmon aquaculture (Mordecai et al. 2021; Reid et al. 2022*a*) have all been implicated in the decline of Pacific salmon (Cohen 2012). Further, climate change is an additional stressor to salmon and their habitats (Healey 2011; Munsch et al. 2022). Even seemingly small impacts on the landscape, when repeated or combined with other stressors over time and space, can contribute incrementally to substantial cumulative harm and negative effects on salmon and salmon habitat (Reid 1993; CCME 2014). As a result of these cumulative stressors, many salmon populations are declining, causing harm to fishing economies (Walters et al. 2019) and food security and food sovereignty (Whyte 2017; Marushka et al. 2019).

The problem of cumulative effects arises through the processes and structures of governance that enable, authorize, or disregard the activities that cause harm to salmon ecosystems (Hannam 2001). Thus, activities and the stressors those activities cause result directly and indirectly from decisions that are produced by complex governance, including laws, policies, decision-making, and information gathering. For example, in British Columbia (BC), Canada, there are overlapping and sometimes competing jurisdictions of international, federal, provincial, local, and Indigenous governments. This complex landscape of governance can also lead to regulatory gaps. Environmental degradation may also occur due to failures to enforce regulations and lack of accountability (Fleischman et al. 2014). For instance, an audit of habitat compensation projects across Canada revealed probable violations of the Fisheries Act 1985 for half of the projects, such as via illegal disposal of pollutants (Quigley and Harper 2006). While some harms may arise from poor compliance, many impacts appear to be authorized by Crown laws and policies;

federal and provincial governments continue to approve activities that put fish habitats at risk (Third et al. 2021; Carlson and Baylis 2023).

Over time, Crown governments (Table 1) have given increasing attention to the consideration of cumulative effects in environmental assessment legislation for large projects. For example, the federal Fisheries Act 1985 included cumulative effects as a consideration when it was amended in 2019. In addition, there are renewed mandates for land-use planning in BC, and emerging federal and provincial laws and policies regarding biodiversity and ecosystem health (Ministry of Land, Water, and Resource Stewardship 2023). Further, in light of the *United Nations Declaration on the Rights of Indigenous Peoples* (UNDRIP 2007) and the provincial and federal commitments to implement that declaration over time (DRIPA 2019; UNDA 2021), Crown governments have a mandate to uphold Indigenous Peoples' rights and titles in decision-making that affects their territories and to obtain free, prior, and informed consent "before adopting and implementing legislative or administrative measures that may affect them" (UNDRIP 2007, Article 19). Thus, despite many barriers within the current Crown governance system, the legal landscape shows early signs of supporting efforts to manage cumulative effects for environmental well-being and environmental justice.

Here, we provide a perspective on cumulative effects in salmon ecosystems at the science-policy interface. Our overarching goal is to advance understanding of connections between multiple stressors for Pacific salmon and related laws and policy levers in BC. First, we provide an integrative synthesis of important stressors to salmon, human activities, and key Crown laws that govern those activities. Second, we present and examine a conceptual model of the cumulative effects management cycle that links the state of salmon ecosystems and governance of human activities in those systems to illuminate overarching barriers and promising opportunities for cumulative effects management in BC. While this paper focuses on BC's salmon ecosystems, there are likely important lessons for the consideration of multiple stressors in a variety of ecosystems, ranging from terrestrial (Collard et al. 2020) to marine ecosystems (Hollarsmith et al. 2022*b*).

We are a group of applied ecologists, practitioners, academics, researchers, and government scientists that have particular interest in salmon social-ecological systems. We assume and assert that salmon ecosystems are an important value for society and thus worth conserving and managing. Throughout the paper, we focus on Crown laws and governance, as these hold up the colonial systems and values that have driven the degradation of salmon ecosystems over the last century or more. We use the term "colonial" to refer to the dominant social-political paradigm in Canada that has enforced and perpetuated systems of power that disrupted Indigenous relationships with each other and the lands and waters of their territories, and in many cases continues to do so today (Whyte 2018). However, we emphasize that the governance landscape in Canada is one of legal pluralism that includes living Indigenous legal orders that predate colonization.

The salmon life cycle: a journey through a multitude of stressors, jurisdictions, and laws

Pacific salmon are migratory species that cross ecological and geographical (and therefore jurisdictional) boundaries throughout their life cycle. The Pacific salmon life history varies considerably among species but begins in the freshwater streams and lakes of the North Pacific Rim, where adult salmon deposit their fertilized eggs (Augerot 2005). Juvenile salmon can remain in freshwater streams, rivers, and lakes for up to several years before transitioning to estuary and nearshore habitats. After migrating to the open ocean, where they reside for 1–5 years, adult Pacific salmon generally return to the streams and lakes where they were born to complete their life cycle. Thus, salmon rely on, and benefit from, many different habitats across their life cycle.

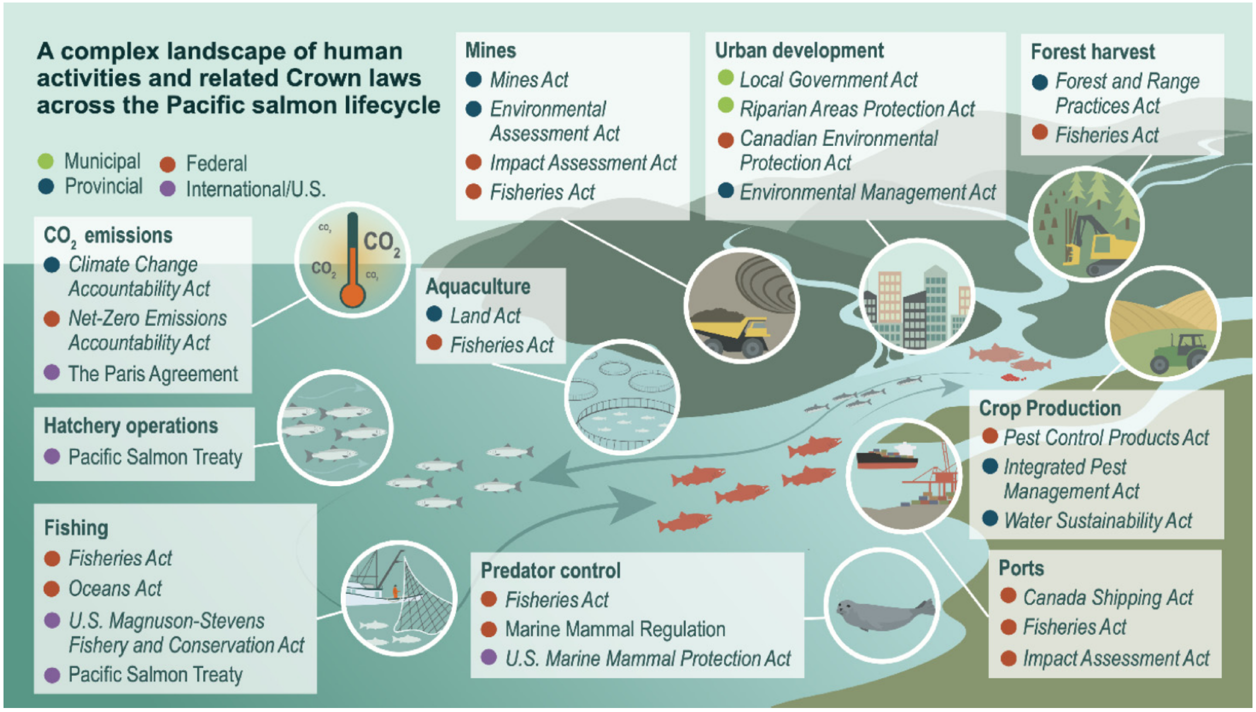
The migratory life history of Pacific salmon also exposes them to multiple stressors. Stressors to Pacific salmon can originate from many human activities on local and global scales through pathways of effects (Table 1), where activities produce multiple stressors, and stressors affect ecosystem processes and conditions, which in turn link to species or populations. Further, these human activities are regulated by diverse laws and policies across international and domestic boundaries in marine, freshwater, and terrestrial environments.

Below, we provide an integrative synthesis of cumulative effects to salmon (Fig. 1). This overview is organized by the major habitats of the salmon life cycle—watersheds, estuaries, and open ocean—though we consider each habitat in turn, the pathways of effects may span and interact across habitats. For each major habitat, we briefly outline some important stressors that can harm salmon, the human activities that cause those stressors, and key Crown laws that regulate those activities in our study area of British Columbia (Fig. 1). We note that this overview is not exhaustive and that different stressors will have varying importance for distinct salmon populations, and regulation may vary depending on the industry, government organization, or jurisdiction. In addition, the level of detail in our discussion of regulatory aspects may vary, reflecting the varied treatment of cumulative effects across BC's complex policy landscape.

Watersheds

Pacific salmon rely on the connectivity, high water quality, and habitat quality of freshwater ecosystems. Migrating adult salmon need cool river temperatures, sufficient flow, and aquatic connectivity to access different habitats. After finding their way home, spawning adults use habitats with clean gravel and sufficient surface and subsurface water flow for spawning and egg incubation. After emergence, depending on the species and life history, young salmon depend on access to high-quality habitats to feed and rear, from lakes to off-channel ponds to flowing rivers. Rivers are a function of their watersheds, with flows, temperatures, and habitats driven by dynamic watershed processes such as ongoing sediment erosion, transport, and deposition. The unique

Fig. 1. Multiple stressors affecting Pacific salmon across their lifecycle from watersheds to nearshore and estuaries and the ocean. Crown laws and policies that are linked to activities and stressors are shown in boxes, with symbols representing legal jurisdiction. Importantly, this figure focuses on colonial governance of human activities—Indigenous Nations also govern their territories according to their own laws given legal plurality.



qualities of watersheds and the rivers and streams they form also allow for the effects of stressors to accumulate through time, space, or both (Reid 1993; Seitz et al. 2011). For example, activities can occur in different parts of the watershed, yet they may affect conditions in the downstream channels.

Timing and magnitude of water flows

The timing and magnitude of water flows, which are greatly influenced directly and indirectly by anthropogenic activities, can control salmon productivity. For instance, recent studies of stream-rearing salmon populations have shown that years with excessively high flows during the fall and winter can reduce salmon production, presumably through the disturbance of incubating eggs (Ward et al. 2015). In contrast, insufficient flows can also negatively impact salmon populations by decreasing food availability and habitat quantity for rearing juveniles and decreasing habitat access for migrating adults (Crozier and Zabel 2006; Rosenfeld 2017; Warkentin et al. 2022).

Human activities that divert water from streams and groundwater impact the timing and magnitude of stream flow in salmon watersheds. For example, direct water withdrawals from streams and rivers for agricultural, industrial, and municipal use can directly decrease water flow (Poole and Berman 2001; Sergeant et al. 2022). In some watersheds in BC, available water resources are fully allocated (i.e., in use) or are expected to be within 15–20 years (Tam and van der Gulik 2020). Water uses and diversions are mainly regulated in BC by the Water Sustainability Act (WSA) 2014 through licensing. In its decision to grant a new license, the Province of BC considers the cumulative allocation of water (demand) through existing licenses and then uses data about streams and watersheds, as well as field review in some cases, to determine supply (Water Authorization Application Assessment and Processing Guide for Applicants 2019). Since 2014, the WSA requires that impacts to environmental flow needs of streams (i.e., volume and timing of water flow for proper functioning of the aquatic ecosystem) be considered when allocating new licenses, leading to potential refusal or requiring specific conditions (WSA, s. 15). Associated with the WSA, the Environmental Flow Needs Policy 2016 (EFNP) has a risk management framework to evaluate both species sensitivity (including fish) and stream flow sensitivity (including seasonal flow variations that may vary from region to region). A finding of high risk does not mean refusal but triggers a more detailed investigation by provincial regulators before a decision is made. Future climate change impacts on flow regimes are not addressed in the EFNP, although climate change impacts to date may be reflected in the average and annual discharge rates used in the risk management analysis (EFNP 2016).

Additionally, under the WSA, the Province may designate “sensitive streams” where fish populations are at risk because of damage to the aquatic ecosystem of the stream; in that case, regulations may be used to limit water use and diversion for new licences and amendments to existing licences (WSA 2014, ss. 17, 128). As of recently, only 15 creeks and rivers are designated as “sensitive streams” (Water Sustainability

Regulation 2016, Schedule B). For water licence holders, rights to withdraw or divert stream flows may be suspended or modified if a "critical environmental flow threshold" has been reached or is at risk of being reached, or where the survival of a population of fish is threatened (WSA 2014, ss. 86, 88). At present, except for review and amendment of individual licenses at 30-year intervals (WSA 201r, s. 23), these temporary orders are the only means to enable management actions that include existing authorizations to ensure adequate flows for salmon at a watershed scale. One exception is for watersheds covered by a Water Sustainability Plan and related objectives, an innovation enabled by the WSA (Division 4).

Beyond direct water usage, many human activities also influence water flow regimes. Removal of upland vegetation by forestry and other land-use practices can decrease infiltration of groundwater, resulting in lower stream base flows (i.e., sustained flow of a stream in the absence of direct runoff) and flashier (i.e., frequent and rapidly changing) stream flows (Naiman 1992; National Research Council 1996). Specifically, summer streamflow deficits have occurred decades after forest harvesting, driven by the combination of advanced snow-melt timing and increased transpiration of regenerating forests (Perry and Jones 2017; Winkler et al. 2017; Gronsdahl et al. 2019). Although forestry can affect flows through a variety of routine activities that have hydrological and geomorphic effects across a watershed (see BCFPB 2022), there appears to be no general legal requirement for watershed assessments that could be used to understand and effectively moderate the cumulative effects of forestry activities on stream flows. However, the Province may designate "fisheries sensitive watersheds" under the Forest and Range Practices Act 2002 (s. 150.1) and set objectives restricting the impact of forestry activities to conserve flows necessary for salmon in the designated watershed. While this tool is used selectively (61 watersheds to date; BCFPB 2018), the circumstances for designation typically involve "watersheds with significant downstream fisheries values and significant watershed sensitivity" (Forest and Range Practices Act 2002, s. 150.1). Water Sustainability Plans, discussed above, were enabled in the WSA to improve overall management of human impacts on water flows. Water objectives under these plans could legally affect activities such as forestry, agriculture, industrial, and urban development. Several pilot projects have been undertaken but to date the implementing regulation has not been made.

Federally, the Fisheries Act 1985, as amended in 2019, enables the Minister to make orders to maintain "the flow of water necessary to permit the free passage of fish" and "water flow … sufficient for the conservation and protection of fish and fish habitat" (Fisheries Act 1985, s. 34.3(2)), and to make regulations "respecting the flow of water that is to be maintained to ensure the free passage of fish or the protection of fish or fish habitat" (Fisheries Act 1985, s. 34.3(7)). To our knowledge, no regulations regarding flow for fish passage exist. The *Fisheries Act* also requires that cumulative effects be "considered" if an authorization is made or in the making of regulations (Fisheries Act 1985, s. 34.1(1)(d)). However, policy guidance applies only to individual authorizations and not to overall regulatory impact on the landscape, and it is unclear how decision-making will be connected to outcomes for specific waterbodies or watersheds (DFO 2025).

Human-induced climate change is also profoundly impacting the timing and magnitude of water flows, with potentially negative consequences for Pacific salmon (Healey 2011). Specifically, warming temperatures are reducing regional snowpack, which many watersheds in British Columbia rely on to transition water from wet winters to dry summers (Mote et al. 2003). Thus, many salmon ecosystems experience higher peak flows in the fall and winter due to increased rainfall that can scour spawning gravel, and lower streamflow during summer months, limiting rearing habitat (Goode et al. 2013; Schnorbus et al. 2014; Warkentin et al. 2022). Indeed, climate change is driving many changes across the Pacific salmon life cycle, and we discuss policy levers for limiting greenhouse gases in the final paragraph of this section.

Water temperatures

Pacific salmon depends on cool water temperature across their life cycle. For example, excessively warm temperatures cause high mortality events during adult migration to spawning grounds, or can also delay migrations (Martins et al. 2012; von Biela et al. 2021). In addition, warmer temperatures accelerate development during incubation, leading to diminished survival in subsequent life stages (US EPA 2003; Burt et al. 2012) and may reduce the amount of suitable freshwater rearing habitat (Mantua et al. 2010).

Industrial activities that release effluent at high temperatures can affect the temperature of streams (Cuddihy et al. 2005). This type of release is regulated by the provincial Environmental Management Act (EMA) 2003 and Water Quality Guidelines (BC Ministry of Environment and Climate Change Strategy 2023). More difficult to identify, monitor, and regulate are the impacts of nonpoint source activities that cumulatively lead to higher temperatures in streams, such as the loss of riparian vegetation. For example, the removal of riparian vegetation through forest harvesting increases the amount of solar radiation reaching streams, which can increase water temperatures by up to 6 °C (Wondzell et al. 2019). BC forestry regulations characterize streams by size, from the largest S1, to the smallest, S6. Logging operations are not required to leave any trees standing along small streams (S4, S5, or S6; Forest Planning and Practices Regulation 2004, s. 47(4)), even though on average small streams make up 70%–80% of the total drainage area of watersheds (BCFPB 2018). Further, current water temperatures in BC's salmon ecosystems appear to be warmed by current and past logging (Cunningham et al. 2023). Under the *Forest and Range Practices Act*, there is a "temperature sensitive stream designation" (Government Actions Regulation 2004), which can offer site-level protection for trees adjacent to the designated portion of the stream to manage temperature for the protection of fish, but this designation does not appear to have been used (BC Ministry of Environment and Climate Change Strategy 2024).

In the more densely urbanized parts of BC, including southern Vancouver Island, the Lower Mainland, and the Thompson Okanagan, the provincial Riparian Areas Protection Act 1997 requires riparian buffers for fish-bearing streams where adjacent land is being developed (and redeveloped). However, there is no equivalent regulation for farmlands within the Agricultural Land Reserve, even though these lands are often located in fertile floodplains, which historically would have been the location of networks of wetlands and waterways. Finally, the *Fisheries Act* prohibits harm to fish habitat, unless authorized, and as a matter of policy, DFO considers riparian buffers along fish-bearing streams (or streams that flow into fish-bearing streams) to be fish habitat (DFO 1993).

Increasing global temperatures continue to warm lakes and rivers, which poses significant risks to cold-adapted fishes like Pacific salmon (Wenger et al. 2011). Global climate change further imposes fundamental alterations to salmon watersheds through losses of glacier inputs and regional shifts from snow-dominated to rain-dominated hydrographs (Nolin and Daly 2006). These changes will cause significant warming among watersheds and, depending on where these changes occur, lead to drastic reductions in available habitat or new local opportunities for salmon to colonize emerging habitat after glaciers recede (Dunmall et al. 2022; Tonina et al. 2022; Iacarella and Weller 2023). Overall, it appears increasing temperatures will pose significant risks to many salmon populations. Again, we discuss policy levers for reducing greenhouse gases in the final paragraph of this section. Locally, temperature increases in streams may also be mitigated by measures to maintain flows, groundwater discharge (Poole and Berman 2001; Hester and Doyle 2011; Ulaski et al. 2023), and riparian shading through policy levers discussed above.

Sediment

Excessive fine sediments in streams can also have detrimental impacts on salmon populations, for example, by suffocating eggs during incubation (Jensen et al. 2009). The amount of fine sediment in streams can be elevated due to forest harvesting which can increase the amount of sediment transported into streams by destabilizing banks and steep slopes (Tschaplinski and Pike 2017). Sediment is also delivered into streams from poorly built or maintained resource roads (BCFPB 2020). In applying the *Fisheries Act*, federal regulators consider sediment a harmful substance when it is deposited in fish-bearing streams, and the practice is prohibited (s. 36(3)) unless specifically authorized. Yet according to the BC Forest Practices Board, the issue of cumulative impacts of sediment from resource roads needs further provincial regulation and policy for forestry activities (BCFPB 2022). At the local level, many municipalities in BC now have bylaws (using powers under the Local Government Act 2015) that require land development activities to control sediment and erosion on construction sites to avoid sediment being carried into stormwater systems, which ultimately drain into streams and waterways.

Pollutants

Across multiple life stages in freshwater, Pacific salmon are susceptible to many different pollutants from nonpoint source pollution, such as urban runoff and direct sources such as industrial development (Ross et al. 2013). In general, the provincial Environmental Management Act 2003 (EMA) regulates point sources of industrial and municipal waste discharge and pollution. This includes waste discharges from activities related to municipal services, agriculture, aquaculture, oil and gas extraction, mining, pulp and paper mills, and pipelines Under the EMA, the Minister develops water quality guidelines that are applied generally and then authorizes allowable types and quantities of waste that can be discharged (EMA 2003, s.6 and regulations). The EMA also prohibits people from introducing certain pollutants into streams and wells (EMA, ss. 46, 59).

In addition to regulating point sources of contamination through water quality guidelines and permitting, the province also develops water quality objectives for priority water bodies, which are intended to support decision-making about resource management and land use and long-term watershed planning (EMA 2003, s.5). Provincial policy notes that these objectives are likely to be more stringent than water quality guidelines because they are intended to safeguard water quality considering future land uses and cumulative effects (BC Ministry of Environment and Climate Change Strategy 2021; Water Quality Objectives Policy 2021). Indigenous nations are also invited to participate in the development of objectives. Once established, water quality objectives must be considered in statutory decision-making by the Ministry, although they are not legally enforceable themselves.

More broadly, the federal government also lists and regulates specific toxic substances under the Canadian Environmental Protection Act 1999, which can mean prohibiting or restricting their use. However, this approach is challenged by the hundreds of new chemicals reaching the market every year. For instance, chemicals from worn car tires can cause pre-spawn mortality in coho salmon spawning in urban streams (Tian et al. 2021; French et al. 2022). However, use of the offending chemical, 6PPD-quinone, is not restricted and is transported by urban run-off, which itself is a nonpoint source of many pollutants to streams that is not directly regulated in BC.

Agriculture is a major source of pollutants, such as pesticides, that can harm Pacific salmon (Baldwin et al. 2009; Ross et al. 2013). Run-off from agricultural land is regulated by the BC Code of Practice for Agricultural Environmental Management 2019, which requires riparian setbacks for certain structures and operations (which does not include protection of riparian vegetation) and restricts applications of nutrients in periods of high precipitation that make it more likely that nutrients will end up being washed into streams and waterways. Further, pesticides are regulated under the Pest Control Products Act 2002 (PCPA), with the federal government deciding which pesticides should be registered for use in Canada. The BC Integrated Pest Management Act 2003 (IPMA) classifies different kinds of pesticides, once registered by the federal government, and sets conditions for their use. Finally,

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local governments can prohibit the use of cosmetic pesticides under the Community Charter (2003).

Similarly, mining activities can degrade water quality with pollutants—from chronic low-level metal leaching and acid mine drainage to the catastrophic impacts of tailings storage dam failures (Sergeant et al. 2022). Provincial regulators aim to manage the risks of highly consequential impacts from permitted activities, such as mining, by permitting and regular inspections (Mines Act 1996). Events such as the Mt. Polley and Victoria Gold's Eagle Gold Mine disasters show that regulations are not always successful. The federal government also regulates the discharge of pollutants into water while considering potential harm to fish and generally prohibits the deposit of harmful substances unless specifically authorized or regulated (Fisheries Act 1985). This includes specific regulation of effluents related to certain types of mining (metals and diamonds), pulp and paper, and municipal wastewater (e.g., Metal and Diamond Mining Effluent Regulations 2002). In effect these regulations can approve the release of pollutants that are known to have harmful effects (Fisheries Act 1985, s. 36(3)–(6); Office of the Auditor General of Canada 2018; Imhof et al. 2021).

Habitat structure

The structure of Pacific salmon habitat in freshwater is directly linked to watershed processes, such as the transport of water, wood, and sediment. Stream complexity and large woody debris form the physical structure of rivers and provide important overwintering habitat for juveniles (McMahon and Hartman 1989; Tschaplinski and Pike 2017). However, habitat structure has been severely degraded by multiple human activities, both by fundamentally altering watershed processes and through direct effects on water bodies.

For example, forest harvesting decreases the input of large woody debris to streams, reducing in-stream complexity and rearing habitat quality for juvenile salmon (Reeves et al. 2003; Tschaplinski and Pike 2017). Similarly, the removal of riparian vegetation can enable sediment inputs that alter channel morphology by shifting a stable sinuous gravel-bed river to an unstable braided morphology (Pike et al. 2010). As discussed above, riparian vegetation protection from forestry activities does not apply to smaller streams that make up 70%–80% of the total drainage area of watersheds. In general, the impacts from forestry and other industrial activities are not assessed and regulated at a watershed or landscape scale, meaning that cumulative effects produced by these activities are not well understood. Two examples of policy options that have only been narrowly applied are "fisheries sensitive watersheds" (Forest and Range Practices Act 2002) and water quality objectives for specific waterbodies or watersheds (Water Quality Objectives Policy 2021).

A significant reduction of suitable habitats has occurred across much of the Pacific salmon range, impacting juvenile production and reducing freshwater productivity (Groot and Margolis 1991; Bradford et al. 1997; Sharma and Hilborn 2001; Buonanduci et al. 2025). Habitats in many productive coastal lowlands have been altered in such a way that systems are barely recognizable compared to 150 years ago (Beechie et al. 2001). For example, agricultural activities have drained wetlands and used dikes to disconnect rivers and streams from floodplain and off-channel habitats (Beechie et al. 1994; Finn et al. 2021). Other activities, like mining, have destroyed entire stream reaches while dams have removed access to large portions of cold-water habitat (Munsch et al. 2022; Sergeant et al. 2022). However, federal and provincial laws generally do not address historic degradation of habitat structure and quantity and the need for rehabilitation. For example, in the Lower Fraser alone, flood infrastructure and other structures are estimated to block salmon access to over 1700 km of streams (Finn et al. 2021). Although the Fisheries Act 1985 includes a prohibition on obstructing fish passage, the minister must enforce this prohibition, which has not been done (Carlson and Baylis 2023).

While there are extensive regulations of specific activities, there are limited landscape-scale protections of habitat that account for the accumulation of incremental harms. Federal and provincial environmental assessment regimes (i.e., Environmental Assessment Act 2018; Impact Assessment Act 2019) provide opportunities to consider the impacts of large projects on watershed health. Both statutes also include provisions related to regional assessments (EAA 2018, s. 35; IAA 2019, ss. 92–103) that could potentially inform decision-making more holistically across watersheds, but to date, these provisions have not been formally enacted in BC. At the local level, municipal governments develop forward-looking plans to shape development within their jurisdictions, which can include urban containment boundaries, but they are also faced with legal and public pressures to densify and develop (Housing Statutes (Residential Development) Amendment Act 2023), which mandates densification to address housing affordability). Provincial land-use planning can also provide an opportunity to shape development strategically at the watershed scale. Land use plans guide which activities can happen where and under what conditions. Specifically, a combination of management goals, objectives, and spatial zoning provide more precise information about permissible activities and management intent in different areas. As BC seeks to "modernize" existing land-use plans and their planning processes, new land use planning principles have been developed to support planning partnerships between the Province and First Nations (Government of BC 2024*a*).

Estuaries and nearshore

As juvenile salmon migrate to the ocean, they pass through estuaries and nearshore habitats. Estuaries are dynamic ecosystems that connect freshwater and ocean environments and thus face effects of human activities in both the land and sea (Hodgson et al. 2020). Depending on the species and population, juvenile salmon may pass through these habitats quickly, but for some populations, estuaries are an important transition habitat where juveniles grow rapidly, prepare for migration to the sea, and possibly avoid predation (Healey 1982; Arbeider et al. 2024). In general, larger smolts tend to have higher marine survival (Holtby et al. 1990; Duffy and

Beauchamp 2011; but see Ulaski et al. 2020), thus growth in estuary habitats has the potential to benefit salmon in the marine environment (Chalifour et al. 2019; Sawyer et al. 2023*a*).

Pollutants

Estuaries and nearshore areas may receive high levels of pollutants and pathogens from industrial (e.g., mining, smelting, and shipping) and agricultural activities (Hodgson et al. 2020), which can negatively impact migrating salmon. Pacific salmon are particularly vulnerable to pollutants during the physiological transition from freshwater to seawater (Ross et al. 2013). Lower adult returns are associated with smolts that migrated through contaminated estuaries (Meador 2014). Estuary and nearshore pollution are regulated by both federal and provincial governments in much the same way as in freshwater (e.g., Fisheries Act 1985; Canadian Environmental Protection Act 1999; Environmental Management Act 2003). For example, the Tsleil-Waututh Nation led the development of new water quality objectives for Burrard Inlet in partnership with the Province of BC (British Columbia Ministry of Environment and Climate Change Strategy and Tsleil-Waututh Nation 2024). Further, the newly introduced BC Coastal Marine Strategy intends to establish such objectives for "coastal areas of concern", which will link to estuary and stormwater management plans (B.C. Marine Coastal Strategy 2024). Further, pollution from industries such as shipping remains a significant issue in nearshore environments (Lloret et al. 2021). Specifically, regulations governing the disposal of sewage and hazardous materials from cruise ships in waters off British Columbia's coast are much weaker (under Canada Shipping Act 2001 and Vessel Pollution and Dangerous Chemicals Regulations 2012) than those in U.S. waters, incentivizing ships to discharge wastewater during Canadian transit and stopovers (Demyen 2021).

Predation

Predation of juvenile salmon is a significant source of mortality, exacerbated by anthropogenic actions in estuaries. While turbid zones may serve as refugia, estuaries are abundant with predators of juvenile salmon, including piscivorous birds, resident fish, and pinnipeds (Thorpe 1994). In fact, birds consume about 3%–4% of migrating juvenile sockeye and Chinook salmon in the Columbia River, and predation of Chinook salmon by pinnipeds in Puget Sound can surpass commercial fishing catches (Evans et al. 2012; Chasco et al. 2017). Industrial activities, such as island formation and log booms, can aggregate predators (Moore and Berejikian 2022), while piers and jetties act as movement barriers for salmon, potentially increasing their predation risk (Munsch et al. 2014). Marine coastal activities, such as log booms, wharves, and marinas, require provincial authorization (Land Act 1996), while some activities are also regulated by the federal government. For example, both federal and provincial environmental assessments were required for the recent authorization of Roberts Bank Terminal 2 at the mouth of the Fraser River. The potential for direct management (i.e., harvest or culling) of pinnipeds for salmon recovery is controversial and made even more challenging by current legal protections such as the U.S. Marine Mammal Protection Act 1972 as well as the Marine Mammal Regulations 1993 (Fisheries Act 1985; Marshall et al. 2016).

Pathogens

Aquaculture can also increase the number of pathogens that young salmon are exposed to during migration. For example, intensive salmon farming provides better conditions for growth and transmission of sea lice (*Lepeophtheirus salmonis* and *Caligus clemensi*) compared to natural conditions, and net pens are often situated on migration routes of wild salmon. Indeed, the productivity of pink and coho salmon populations was negatively associated with sea lice abundance on salmon farms compared to regions with no farms (Krkošek et al. 2011; Cohen 2012; Krkošek et al. 2024). Aquacultural transmission of viruses such as Piscine orthoreovirus (PRV) from Europe poses another threat to wild salmon in British Columbia (Mordecai et al. 2021). The operation of salmon farms within the migratory routes of Pacific salmon is licensed under federal authority (Fisheries Act 1985; Pacific Aquaculture Regulations 2010) and jointly regulated with the Province of BC, which is primarily responsible for tenures related to the siting of salmon farms (Land Act 1996; Canada-British Columbia Agreement on Aquaculture Management 2010).

Given concerns about impacts to wild salmon, the Crown has announced a transition away from open-net salmon farms (DFO 2024). For example, farms were halted in the Broughton Archipelago through a joint decision-making process between the Province and the Namgis First Nation, the Kwikwasut'inuxw Haxwa'mis First Nations and Mamalilikulla First Nation to protect migrating juvenile Pacific salmon. Similarly, at the time of publication, the Fisheries Minister will not renew licenses for 15 salmon farms in the Discovery Islands, BC and those holding licenses to operate open net-pen salmon aquaculture in BC will have to fully terminate operations by 30 June 2029.

Habitat quality and quantity

Like freshwater habitats, environmental factors like flow, temperature, and connectivity in estuaries are also vital for Pacific salmon (Kjelson et al. 1982; Hodgson et al. 2020; Davis et al. 2022). Estuaries are connected to upstream watersheds; thus, managing human activities that affect hydrology within watersheds can also have indirect impacts on conditions in estuaries. The many activities that affect flow and temperature in estuaries, such as dam construction, water diversions, land use, and the effects of climate change, have similar policy levers (and gaps) as described for watersheds above. Additionally, habitat connectivity is critical; however, approximately 85% of tidal wetlands have disappeared in the Fraser River estuary from dikes and extensive development (Boyle et al. 1997; Brophy et al. 2019). Further, other barriers like jetties and tidal gates reduce access to habitat (David et al. 2014; Gordon et al. 2015; Scott et al. 2016; Brophy et al. 2019). Specifically, coastal dikes span 125 km of the coast of BC's Lower Mainland, with no specific regulation regarding barriers to fish passage (Dike Maintenance Act 1996) and little or no enforcement action has been taken by the federal regulator (Fisheries Act 1985). At the same time, global climate change is resulting in sea level rise, which further reduces estuary habitat (Yang et al. 2015). Indeed, juvenile salmon survival is higher when more of the estuary is in natural condition (Magnusson and Hilborn 2003).

Jurisdictional boundaries in estuaries can be ambiguous (Reference re: Ownership of the Bed of the Strait of Georgia and Related Areas 1984), as coastal regions are managed by all orders of government (Indigenous, federal, provincial, and municipal). On one hand, many conservation tools are available across jurisdictions, such as the provincial designation of Wildlife Management Areas (Wildlife Act 1996), federal Marine Protected Areas (Oceans Act 1996), as well as Indigenous Protected and Conserved Areas (Indigenous Circle of Experts 2018). On the other hand, jurisdictional silos can result in fragmented management that, without a broader coastal strategy, fails to address the cumulative effects of nearshore activities. Some exceptional practices have been undertaken such as the development of marine use plans through partnership between the Province of British Columbia and 17 member First Nations (Marine Plan Partnership for the North Pacific Coast 2024) and BC's first Coastal Marine Strategy (B.C. Marine Coastal Strategy 2024).

Open ocean

After transiting through estuaries and nearshore habitats, Pacific salmon migrate to the open ocean to feed and grow. In general, Pacific salmon tend to migrate north along the coast and then out into the open ocean (Myers et al. 2007), and mortality appears to be intense and size-selective in the period immediately after ocean entry and during the first winter at sea (Holtby et al. 1990). Mortality tends to decline as Pacific salmon grow in the ocean but mortality of returning adults increases again as they migrate back to natal streams and are exposed to predators and fishing mortality along the coast.

Competition

Both competition among Pacific salmon for shared prey as well as ocean conditions can combine to affect salmon productivity. For example, years with greater numbers of pink and chum salmon are associated with lower abundances and sizes of co-occurring species like sockeye salmon (Connors et al. 2020). The mass release of over five billion hatchery salmon into the Pacific Ocean every year to supplement fishing may exacerbate competition for food resources in the ocean (Ruggerone et al. 2023; NPAFC 2024). Ocean conditions, such as upwelling, can also change the abundance of shared prey, strongly affecting salmon growth and survival in the ocean (Koslow et al. 2002; Wells et al. 2016). In general, upwelling off the south coast of British Columbia is occurring earlier and could result in a mismatch between the availability of food and the timing of out-migrating smolts (Wilson et al. 2023). Other impacts of climate change include warming waters in the Gulf of Alaska feeding grounds, which may decrease the amount of optimal habitat as fish avoid high temperatures (Langan et al. 2024). Further, ocean acidification and increases in sea-surface temperatures because of human-induced climate change will alter the abundance and distribution of salmon prey and predators (Karinen et al. 1985; Orr et al. 2005). The effects of these changes on salmon are difficult to predict, but overall, productivity of the North Pacific may decline under global warming (Abdul-Aziz et al. 2011), and these impacts may be exacerbated by the increasing number of salmon competitors in the ocean (Connors et al. 2020; Ohlberger et al. 2022).

While evidence is accruing that competition from hatchery fish in the ocean is leading to decreased productivity of co-occurring wild salmon (Connors et al. 2025), there is little international oversight regulating the release of hatchery fish into the Pacific Ocean. Hatcheries can also pose local challenges to salmon such as through genetic introgression (McMillan et al. 2023). Given that hatchery releases from the various Pacific Rim nations migrate to shared ocean feeding grounds, this represents a common-pool resource and is a major legislative gap with little international cooperation (Holt et al. 2008). Further, the Pacific Salmon Treaty (1985) includes the production of hatchery salmon when allocating harvest and therefore further incentivizes hatchery production (Kibel 2020).

Fishing mortality

Commercial fishing is a significant source of mortality for adult Pacific salmon and has the potential to lead to the collapse of populations without careful management. Pacific salmon are often caught in mixed-stock fisheries, where less-productive stocks may be caught with more productive, co-mingling stocks (Ricker 1958; Moore et al. 2021). Mixed-stock fisheries present a major challenge to the management of fisheries harvest compared to traditional Indigenous terminal fisheries (Atlas et al. 2021). High salmon productivity can make certain populations resilient to high harvest rates, but even low harvest rates can threaten populations if they have been weakened by habitat degradation and climate impacts. Thus, shifts in freshwater and marine conditions, driven by local human activities and global climate change, can increase risks of overfishing by undermining the assumptions underlying fisheries management (Larkin 1977).

In British Columbia, DFO regulates commercial fishing in Canada (Fisheries Act 1985) and has decreased fisheries harvest rates substantially in response to declines in a few populations (Walters et al. 2019). However, salmon that originate in BC are also intercepted by U.S. fleets during their ocean migration from Oregon to Alaska, and fish may be overharvested in these trans-border fisheries. Harvest of Pacific salmon originating from and caught in U.S. waters is regulated under The Magnuson-Stevens Fishery and Conservation Act 1976, and catch is largely determined by numbers of salmon returning to rivers in the US, not Canada.

Thus, depressed BC salmon populations could potentially be overharvested as bycatch in productive Alaskan fisheries (Rosenberger et al. 2022).

The bilateral Pacific Salmon Treaty (1985) was established by both the U.S. and Canada to manage international fisheries and ensure benefits equal to the production of salmon originating in their waters. However, amounts and allocation of harvest to different sectors are controversial and subject to industrial pressures. The Pacific Salmon Treaty has been critiqued as appearing to enable Alaskan harvest of struggling Canadian salmon populations (Rosenberger et al. 2022). In contrast, in 2023, a U.S. federal judge temporarily vacated permits of the summer and winter Chinook troll fishery that intercepts BC salmon on behalf of southern resident killer whales under the U.S. *Endangered Species Act* 1973 (Wild Fish Conservancy v. Rumsey 2023). In addition, the State of Alaska and Canada recently signed a new agreement to halt directed Chinook commercial fishing and recreational fisheries in the Yukon River mainstem and Canadian tributaries for Chinook salmon until 2030 (Agreement of April 1, 2024, regarding Canadian-origin Yukon River Chinook Salmon for 2024 through 2023, 2024). Thus, the harvest of Pacific salmon that originate in British Columbia is determined across vast jurisdictional and spatial scales (Atlas et al. 2021).

Effects of climate change

The effects of climate change pose challenges for salmon across their life cycle, as mentioned throughout this section. Both the BC Climate Change Accountability Act 2007 and the Canadian Net-Zero Emissions Accountability Act 2021 influence the amount of greenhouse gases produced in BC. Internationally, the Paris Agreement (2015) aims to limit global temperature rise this century to below 1.5 °C compared to pre-industrial levels and was ratified or agreed to by 194 states and the European Union. However, global warming of 1.5 and 2 °C will be exceeded during the 21st century unless deep reductions in CO_2, and other greenhouse gas emissions occur in the coming decades (Arias et al. 2021; Canadian Climate Institute 2024). Canada is currently not on track to meet its 2030 target, but policy implementation may decelerate emissions (Sawyer et al. 2023*b*).

The synthesis above reveals that Pacific salmon on their migratory journeys encounter a myriad of stressors, with uncertain levels of protection provided by a range of existing laws and policies. This complexity emerges even though this synthesis was not exhaustive and did not include some stressors that may be important at times (e.g., invasive species, Sanderson et al. 2009). Authorization of many human activities by Crown governments, ranging from industrial forestry to water withdrawals for agriculture and urban development, continues to add to the progressive degradation and loss of salmon habitats, diminished productivity, and reduced survival. While updated laws like the BC *Water Sustainability Act* and Canada *Fisheries Act* offer some avenues for more effective management of impacts, the protection of critical flows and habitat quality remains a challenge, with gaps in addressing indirect impacts such as changes to upland landscapes. Moreover, the complex assortment of laws governing habitat quality and quantity underscores the need for comprehensive, coordinated efforts to safeguard the future of Pacific salmon amidst escalating cumulative impacts.

Barriers and opportunities for managing cumulative effects in salmon systems

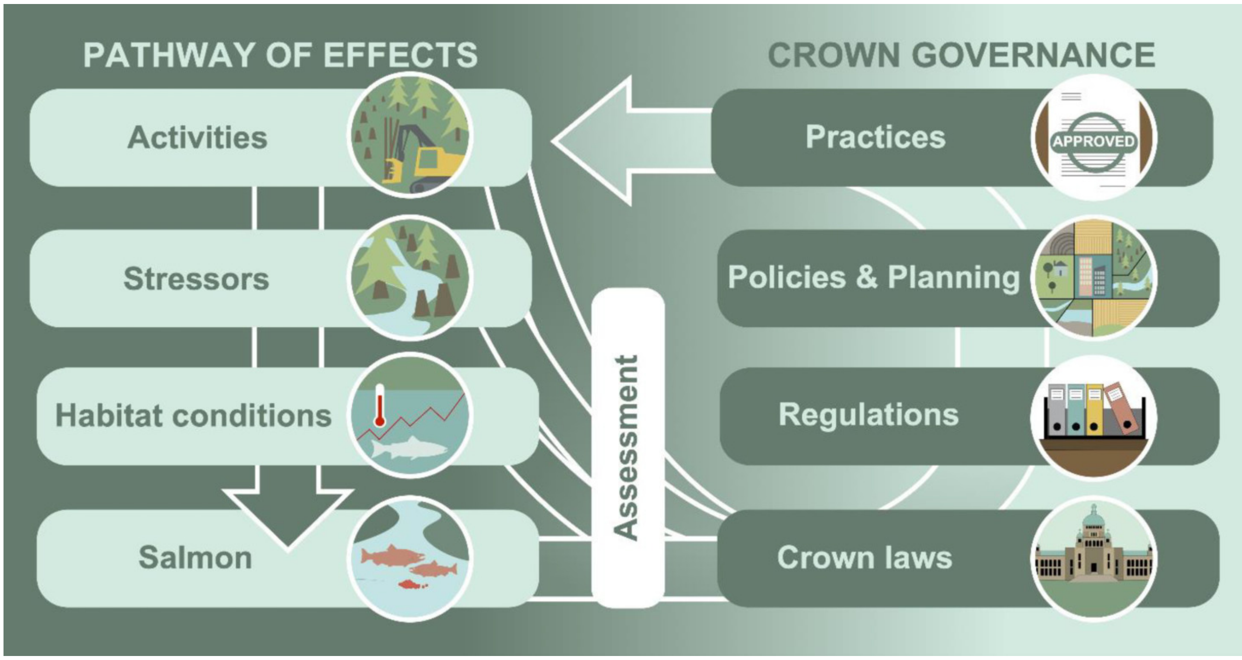
The management of human activities and their cumulative effects on salmon systems can be conceptualized as a feedback loop linking the pathways of human impact, assessment of the state of the ecosystem, and governance (Fig. 2). We refer to this as the cumulative effects management cycle (Table 1). Multiple human activities can generate cumulative effects, either through a single activity causing repeated stressors, a single activity causing various stressors, or multiple activities causing multiple stressors (Foley et al. 2017; Murray et al. 2020). Assessing the state of ecosystems or stressors could then inform regulatory decisions, promoting sustainable development in salmon ecosystems. Consequently, human activities with incremental impacts could be regulated to conserve wild Pacific salmon, assuming this aligns with societal priorities.

Weaknesses in the connections among the components of the cumulative effects management cycle can impair the effective stewardship of ecosystems (Foley et al. 2017; Hollarsmith et al. 2022*a*, 2022*b*; Orobko et al. 2022). Through a discussion informed by a synthesis of the literature and recent legal decisions, as well as expert judgement and experience of our co-authors, we examine the proposed cumulative effects management cycle and identify five key barriers and related opportunities (Fig. 3). In the subsequent text, each numerical barrier can be addressed by the corresponding numerical opportunity.

Barrier 1: monitoring effects from activities to salmon is complex and costly, with mechanisms of impacts that are not always clear

Salmon systems are complex, comprised of many interacting parts, and the effects of human activities on salmon habitat can be difficult to predict. The extent to which salmon systems can be altered while retaining their properties and resilience varies, as systems differ in sensitivity due to geography and physical characteristics (e.g., Lisi et al. 2015; Khan and Fryirs 2020). For example, a meta-analysis by Naman et al. (2024) found that experimental forest harvests had inconsistent impacts on stream ecosystems, with no broadly predictable "safe" level of forestry and limited ability to make generalizable predictions of the impacts of forestry on watersheds. The downstream and downhill movement of water and bi-directional movements of fish through river networks can also propagate cumulative effects through space and time, decoupling activities from their effects (Cunningham et al. 2023). Effects persist over long timescales, with past activities leaving a lasting mark on ecosystems (Wohl 2019). For example, impacts are still evident on many river channels from historic forestry practices in BC (Wohl 2014; BCFPB 2022). The effects of human activities also occur against the

Fig. 2. One conceptualization of the cumulative effects management cycle. This conceptual model shows how information on cumulative effects can inform federal and provincial governance, altering practices, and thus preventing the accumulation of cumulative harm in salmon ecosystems. Although this figure conceptualizes the Crown system of governance, we emphasize that the governance landscape in Canada, as a plural legal society, includes Indigenous legal systems that predate colonization, with living Indigenous legal orders.



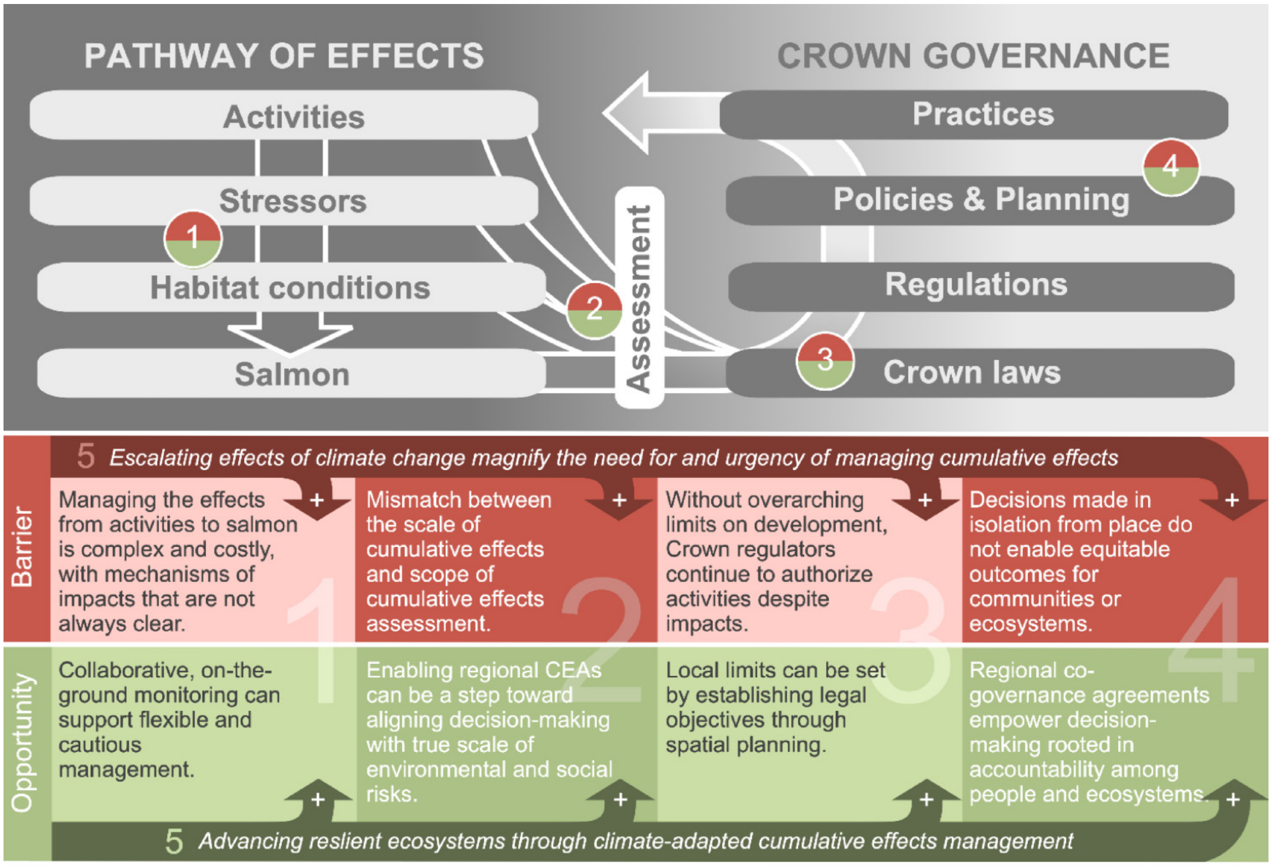
backdrop of stochasticity in both the freshwater and marine environment, which can drive trends in fish productivity or nonstationarity (Lobón-Cerviá and Rincón 2004; Rogers and Schindler 2011). Indeed, the impacts of human activities on salmon habitat may be inherently difficult to predict, as their specific outcomes often depend on complex and dynamic environmental interactions. Even though broader-scale changes to salmon habitat are evident, detecting and predicting the incremental impacts of specific human activities on salmon and their habitats can be challenging and often has steep information requirements.

Effective monitoring can be used to inform regulatory decision-making by both revealing the true state of salmon systems (e.g., accumulated state assessment, Table 1) and resolving the relationships between broad indicators and changes to habitat (e.g., stressor-based assessment, Table 1). However, information on the pathway of effects is scarce or patchy. For example, the simplest way to monitor human development on the landscape is to track the distribution of activities themselves. Yet, data gaps in BC exist including the footprint of mines and the amount of water being used or diverted (Connors et al. 2018; PSF 2024). The effects of activities are also context-specific and rely on broad indicators instead of on-the-ground monitoring, such as equivalent clearcut area representing predicted changes to peak flows (Smith and Redding 2012), and may overlook significant effects (Hou et al. 2024). Overall, monitoring of the state of salmon populations has also been decreasing (Price et al. 2008). While sustainability science indicates that uncertainties should lead to precautionary decision-making (Foster et al. 2000), they may favour decisions that promote, rather than avoid, cumulative effects in salmon systems (Kwasniak 2010). For example, a key Canadian court decision (Pembina Institute for Appropriate Development v. Canada (Attorney General) 2008) enables projects to proceed even when mitigation measures are uncertain. Thus, there are major information gaps on the activities, stressors, and state of salmon and their ecosystems that could otherwise help inform decision-making.

Opportunity 1: collaborative, on-the-ground monitoring can support flexible and cautious management

In the absence of perfect knowledge and predictability about the pathway of effects, how should cumulative effects management proceed (Fig. 3)? One step forward is to continue to invest in and require standardized monitoring to better track human activities, stressors, and the state of salmon systems. This monitoring and associated data systems could come from federal and provincial Crown agencies, other organizations such as the Pacific Salmon Foundation, and local organizations and experts. Collaborations between Crown governments and First Nations can lead to sharing of data and knowledge, advancing our understanding of the state of salmon systems (e.g., SSAF 2021; Reid et al. 2022*b*).However, any such data sharing should proceed with care and inclusivity throughout the cycle of decision-making (Cannon et al. 2024). Second, on-the-ground monitoring can be used to resolve stressor–response relationships (Rosenfeld et al. 2022) and support the identification of

Fig. 3. Barriers and opportunities for managing cumulative effects among connections of a hypothetical conceptualization of the pathway of effects from activities to salmon and the assessment of these effects to inform Crown governance processes. Numbers correspond to barriers and opportunities among components of the pathway of effects and governance system for managing cumulative effects in BC's salmon-bearing watersheds.



leading factors of declines (Dempson et al. 2024). Third, monitoring and assessment can support flexible strategies that promote continuous learning by evaluating legal objectives and benchmarks and modifying plans as situations change (Walters 1986; Millar et al. 2007; Schindler and Hilborn 2015). Finally, given high uncertainty, we suggest that Crown governance adopts a "strong" version of the precautionary principle that requires risk avoidance when the potential for substantial negative effects exists when considering how to apply the results of monitoring to decision-making (Benidickson et al. 2005; Kwasniak 2010).

Barrier 2: mismatch between the scale of cumulative effects and the scope of cumulative effects assessment

Cumulative effects assessment (CEA, Table 1) is primarily defined in regulatory contexts as a process to predict the potential consequences of development projects (Dubé et al. 2013). Currently, CEA is undertaken as part of Environmental Impact Assessment (Jones 2016) and aims to evaluate the combined impacts of proposed projects alongside those of past, present, and reasonably foreseeable future projects (Effects Assessment Policy 2020) as required under British Columbia and federal environmental assessment laws (EAA 2018; IAA 2019). These assessments are primarily stressor-based, in which project-level stressors are identified and their effects on valued ecosystem components is estimated based on known pathways of effects (Beanlands and Duinker 1984; Dubê et al. 2013). However, regulatory CEA is limited in scope, including only "significant effects" of other projects under EA (Regulations Designating Physical Activities 2012; Reviewable Projects Regulation 2019) and ignores potentially far-reaching and long-lasting impacts (Contant and Wiggins 1991; Moore et al. 2015). As a result, CEA misses the cumulative impacts of many small projects and ongoing activities in other sectors such as forestry or agriculture, as well as individually small but potentially collectively important effects (Westwood et al. 2019). Despite criticisms that CEA within environmental assessment is largely ineffective (Dubé 2003; Seitz et al. 2011; Foley et al. 2017), CEA has yet to meaningfully transition to more integrated ecosystem-based approaches (Hodgson and Halpern 2019; Blakley and Russell 2022; Greaves et al. 2025).

The cumulative effects of activities on Pacific salmon are deeply intertwined with the social and cultural dimensions of salmon–people systems and Indigenous Peoples face inequities that threaten these relationships (Carothers et al. 2021). In British Columbia, CEAs often exclude the impacts of development on Indigenous communities and traditional ways of life through a lack of transparency, meaningful engagement and consultation, and respect for Indigenous and local knowledge (Clogg et al. 2017; Adams et al. 2023). This has led to mistrust and harmful outcomes (Booth and Halseth 2011; Eckert et al. 2020). By neglecting Indigenous sovereignty and knowledge, CEAs fail to comprehensively address regional impacts and overlook the broader social-economic consequences for communities and ecosystems (Tulloch et al. 2024).

Opportunity 2: enabling regional cumulative effects assessments can be a step toward aligning decision-making with true scale of environmental and social risks

Regional approaches to assessing cumulative effects are better aligned with the scale at which environmental degradation occurs. Unlike project-specific CEAs, regional assessments use stressor-based approaches to characterize the combined impacts of multiple human activities across sectors and large spatial scales (Harriman and Noble 2008; Adams et al. 2023). However, these assessments may also include other types of evaluations depending on the policy context and objectives, such as accumulated state assessment (Dubé et al. 2013).

Formal regional assessment (Table 1) is a relatively new tool that was introduced both provincially (EAA 2018) and federally (IAA 2019) to move beyond project-specific evaluations and provide a broader understanding of the regional context in which development takes place. Although formal regional assessments have not yet been conducted in British Columbia, their implementation holds promising potential. Many projects that do not trigger formal environmental assessments under the EAA or IAA may still require authorization under the *Fisheries* Act. While regional assessments are not formally required under the *Fisheries Act*, the Act's provision requiring the Minister to consider cumulative effects in decision-making and regulation development creates an opportunity to draw on regional assessment findings. Although clear policies for implementation are still forthcoming (DFO 2022), this requirement signals a growing commitment to integrating broader environmental considerations into regulatory decisions.

The provincial Cumulative Effects Framework (CEF; CEFIP 2016) in BC is another emerging tool for regional assessment of cumulative effects across natural resource sectors. Operating outside of Environmental Assessment legislation and processes, the CEF provides a broad-scale view of landscape conditions that could inform how permitting and decision-making powers are applied. The CEF approximates the pathway of effects model (Fig. 2) by linking indicators (e.g., roads, stream crossings) to ecosystem components (e.g., water quantity, water quality, and aquatic habitat), and ultimately to values (e.g., aquatic ecosystems; PAETWG 2020). These values are often region-specific, grounded in provincial legislation, regulations, and agreements with First Nations. While the CEF offers significant potential to guide cumulative effects management, a key uncertainty is whether it will carry regulatory weight as it is not legally binding (see Barrier 3).

In addition to better aligning with the ecological scale of cumulative effects, regional assessments can support decision-making that reflects the governance structures and values of the regions in which development occurs. By operating at a broader spatial scale, regional assessments can account for cumulative impacts across multiple activities and jurisdictions, while recognizing and incorporating Indigenous values, rights, risk tolerances, and jurisdiction (Ho-Tassone et al. 2023). For instance, researchers and three First Nations in the Central Coast of British Columbia collaborated to develop a spatial model that integrates Indigenous knowledge and participatory tools into governance processes, ensuring that ecosystem-based management prioritizes both ecological health and cultural values (Tulloch et al. 2024). This type of approach offers an opportunity for co-developing assessments in line with BC's commitment to UNDRIP (2007) and First Nations (see Adams et al. 2023), while also providing a foundation for achieving free, prior, and informed consent (Declaration Act Consent Decision-Making Agreement for Eskay Creek Project 2022; Declaration of the Rights of Indigenous Peoples Action Plan 2022–2027 2022; Adams et al. 2023). If regional assessments (e.g., through the CEF or EA) can connect to enforceable limits, they could represent a significant step forward in ensuring decision-making reflects the true scope of environmental and social risks.

Barrier 3: without overarching limits on development, Crown regulators continue to authorize activities despite impacts

Across the multitude of policies that regulate activities, there are few examples of enforceable limits of cumulative effects (Lamb et al. 2024; Murray et al. 2025). If there are not clear limits for how much net harm is allowed, decision-makers may continue to approve projects that cause incremental impacts. Both federal and provincial laws reference the cumulative effects of human activities and require "consideration" of these effects in decision-making but may be inadequate in practice (e.g., Fisheries Act 1985; IAA 2019). For example, in Environmental Assessment, if government-defined thresholds (such as water quality parameters) are already exceeded, assessors may deem project impacts insignificant, reasoning that the high baseline (Table 1) minimizes further effects (Murray et al. 2018). Further, the Fish and Fisheries Habitat Program draft position on cumulative effects (DFO 2019) suggests that amendments to the *Fisheries Act* will not add additional consideration of effects at the watershed scale. Thus, many small projects can occur on fish and fish habitat without considering the net harm (DFO 2019). Current legislation nor other provincial government directives explicitly or effectively require government regulators to manage cumulative effects when authorizing the use of natural resources as evidenced by the Auditor General's audit (Bellringer 2015) and the Yahey v. British Columbia (2021) decision. For example, in the Yahey v. British Columbia decision, Blueberry River First Nations saw the BC Cumulative Effects Framework as "fundamentally flawed as it does not set thresholds, alter existing decision-making processes, or create any new legal requirement", which was echoed by the

Court, which found the province's treatment of cumulative effects to be "business as usual, as applicable legislation and policy remained unchanged".

The Canada *Species at Risk Act* (SARA 2002) could provide powerful protection that gives salmon a voice by protecting critical habitats. However, the process of listing species under SARA is very slow and can be influenced by political and economic interests (Turcotte et al. 2021). For example, species targeted in commercial or recreational fisheries are unlikely to be listed under SARA (Mooers et al. 2007). At the time of publication, no population of Pacific salmon has been listed under SARA, despite an independent science advisory panel (COSEWIC) designating 24 Pacific salmon population as Endangered, and 10 populations as Threatened (Government of Canada 2023). Further, endangered species laws do not necessarily prevent cumulative effects but rather serve as a "last lifeline" for species to prevent extinction after there has already been great harm to the species and benefits it provides to people (Lamb et al. 2023).

Opportunity 3: local limits can be set by establishing legal objectives through spatial planning

Spatial planning has the potential to provide a holistic and integrative framework for managing cumulative effects on an ecologically relevant scale, overcoming some of the major flaws in project-based planning. Approximately 85% of British Columbia is covered by some level of provincial land use plan (Ministry of Forests, Lands, Natural Resource Operations, and Rural Development 2021), and marine and coastal plans have also been developed. Land use objectives become legally enforceable when legal orders are made in respect to particular objectives under the authority of the Land Act 1996, the Forest and Range Practices Act 2002, the Oil and Gas Activities Act 2008, the Environment and Land Use Act 1996, the Wildlife Act 1996, and the Protected Areas of British Columbia Act 2000. For example, the Great Bear Land Use Objectives Order 2016 drew on the Central Coast Land & Resource Management Plan as well as land use plans developed by First Nations and brought into law a range of land use objectives related to forestry for the region (Curran 2017). In 2018, the province also initiated a new planning framework (i.e., modernized land use planning) in partnership with First Nations that is intended to address complex issues of cumulative effects and climate change. However, the process has been slow to produce tangible products, with only six plans in development (Government of BC 2024*b*). Second, the first Water Sustainability Plan will be developed for the Xwulqw'selu (Koksilah) watershed over the next three years through a government-to-government agreement between Cowichan Tribes First Nation and the Province of BC (Xwulqw'selu Watershed Planning Agreement 2023). Similarly, the Upper Nicola Band of the Okanagan (Syilx) Nation and the Lower Nicola, Coldwater, Nooaitch, and Shackan Bands of the Nlaka'pamux Nation as well as the Province of BC intend to establish a government-to-government partnership to develop a Water Sustainability Plan (Nicola Watershed Pilot Memorandum of Understanding 2018). Thus, there will soon be practical examples of these plans and how they might be used to manage cumulative effects of activities on flooding and drought in salmon watersheds. As well, BC is co-developing a Biodiversity and Ecosystem Health Framework that aims to uphold the *United Nations Declaration on the Rights of Indigenous Peoples* (UNDRIP 2007) and BC's *Declaration on the Rights of Indigenous Peoples Act* (DRIPA 2019) and provide an overarching standard of protection for biodiversity and ecosystem health in the province that would inform laws, policies, and actions (Ministry of Land, Water, and Resource Stewardship 2023).

Barrier 4: decisions made in isolation from place do not enable equitable outcomes for communities or ecosystems

Centralized decision-making systems in British Columbia often fail to align with the realities of local communities and ecosystems, leading to inequitable outcomes and unsustainable resource management. Crown agencies are often both relationally and spatially disconnected from each other and from the people and ecosystems that bear the consequences of cumulative effects on salmon populations (Moore et al. 2015; Adams et al. 2023). This disconnection results in several systemic challenges. First, the spatial breadth and ecological complexity of ecosystems demand localized, nuanced approaches that centralized systems are not equipped to provide over the long term (Dietz et al. 2003; Berkes et al. 2006; Kobluk et al. 2024). Second, responsibilities for managing resource-related activities and their threats are fragmented across various agencies, limiting the oversight needed to address overlapping and interacting impacts on salmon and their habitats. For example, as highlighted in the Yahey v. British Columbia decision, this fragmentation results in disconnected, piecemeal approvals of activities that enable cumulative effects. Third, when restricting resource extraction entails significant political costs, decision-makers may prioritize short-term political gains over long-term sustainability. This approach has led to notable failures, such as the collapse of the Atlantic cod (*Gadus morhua*) fishery (Gezelius 2002; Hutchings and Myers 1994). Finally, the exclusion of Indigenous knowledge holders and their governments from Crown-regulated processes remains a significant barrier to achieving equitable outcomes. Without integrating Indigenous perspectives and governance structures, natural resource decision-making is often misaligned with the needs of people, watersheds, and ecosystems (Booth and Skelton 2011; Clogg et al. 2016; Eckert et al. 2020). Addressing these challenges requires governance systems that are connected to place, inclusive of diverse knowledge systems, and capable of adapting to ecological and community-specific needs.

Opportunity 4: regional co-governance arrangements and Indigenous-led approaches empower decision-making rooted in accountability among people and ecosystems

Resurgent Indigenous leadership and emerging regional co-governance arrangements offer transformative approaches to decision-making, grounded in accountability among people, places, and ecosystems. While there is enormous diversity of Indigenous Peoples and cultures across BC and beyond, these approaches are often holistic and interconnected and informed by refined knowledge and monitoring practices (Brown and Brown 2009; Reid et al. 2022; Adams et al. 2023; Artelle et al. 2021). Collectively, these governance models ensure stronger connections between pathways of effects and governance processes in place that can truly address those pathways of effects. For example, Indigenous governments and their communities continue to take care of salmon and assert their rights as stewards of their lands and waters (Brown and Brown 2009; Atlas et al. 2017; Steel et al. 2021). A few examples include Indigenous Protected and Conserved Areas (Tran et al. 2020), self-determined land use plans (e.g., Tla'amin Land Use Plan 2010), and fisheries management plans (Ban et al. 2019; Atlas et al. 2021).

Indigenous Peoples are formally recognized as rights and title holders and as authorities with inherent jurisdiction in their territories by Crown governments in British Columbia (R. vs. Sparrow 1990; Tsilhqot'in Nation v. British Columbia 2014; DRIPA 2019), but the implementation of this recognition in practice is variable. There are increasing examples of Indigenous governments leading or entering into co-governance relationships with Crown governments, which offer opportunities for the joint stewardship of salmon and management of cumulative effects. For example, Crown governments and First Nations are engaging in government-to-government agreements, from Strategic Engagement Agreements (Government of BC 2024*c*) that establish mutually agreeable procedures for consultation, to Reconciliation Agreements (e.g., Coastal First Nations Reconciliation Protocol Amending Agreement 2017), to Foundation Agreements, which establish a shared long-term vision to implement Indigenous rights and title with defined milestones (Lake Babine Nation Foundation Agreement 2022). These agreements or funding opportunities currently work towards improved fish harvest practices (e.g., Fisheries Resources Reconciliation Agreement (FRRA) 2021, Indigenous Watersheds Initiative 2023) and land and marine use practices (e.g., *Wóoshtin Yan Too Aat* : Land and Resources Management and Shared Decision-Making Agreement (2011); Diggon et al. 2022; Canada British Columbia MPA Network Strategy 2023). The mechanisms provided by the *Declaration of the Rights of Indigenous Peoples Act* (DRIPA 2019, s. 7) and advancements in shared decision-making through land use planning over the past two decades also demonstrate a commitment to collaboration. Notably, the S7 Consent Decision Making Agreement for Eskay Creek stands as an example of a DRIPA (2019) agreement between BC and the Tahltan Central Government that requires the Nation's consent to ministerial approval for the Eskay Creek gold and silver mine revitalization project (Gilmour 2023). Moving forward, the implementation of the necessary legislative amendments outlined in the Declaration of the Rights of Indigenous Peoples Action Plan (2022), such as the court order to modernize the *Mineral Tenures Act* (Gitxaala v. British Columbia (Chief Gold Commissioner) 2023) offers a promising opportunity to further solidify consent-based decision-making across the province.

Barrier 5: escalating effects of climate change magnify the need for and urgency of cumulative effects management

The escalating effects of climate change heighten not only each of the barriers we have discussed above but also the urgency to move toward effective cumulative effects management (Fig. 3). Climate change transforms any local pressure into a cumulative impact. For example, wildfires are increasing in frequency and intensity both because of climate change and the effects of 150 years of industrial logging, fire suppression, and reforestation practices in BC (Parisien et al. 2023). The effects of climate change can thus increase the risks of activities through changes in temperature and frequency of disturbances like wildfires, floods, and droughts (Pike et al. 2010; Parisien et al. 2023). It is unclear how cumulative effects assessments, either through EA or the provincial CEF, incorporate added climate impacts in their risk assessments. Indeed, Crown environmental laws and policies developed during the "climate normal" period have not been sufficient to manage cumulative impacts and may be greatly insufficient to protect ecosystems and salmon that are now also coping with various harms of climate change (Moore et al. 2023). For example, previously developed management objectives and benchmarks (Table 1) for water use may not account for the added, sometimes interactive, effects of climate change such as the projected 30% decrease in snowmelt in the Fraser River basin by mid-century. We emphasize the importance of considering the cumulative effects of both climate change and local human activities, including land-use decisions, as local actions can either erode or promote the resilience of salmon systems to climate change (Moore and Schindler 2022). Finally, as local communities are challenged to adapt to climate change, with Indigenous Peoples disproportionately affected (Jacob et al. 2010), the importance of place-based and equitable decision-making will be more important than ever (Delevaux et al. 2019; Whitney and Ban 2019).

Opportunity 5: advancing resilient ecosystems through climate-adapted cumulative effects management

The overview of the current approaches to assessment and regulation of cumulative effects showcases overall failures in the governance system and the need and opportunity for an integrated policy approach. We suggest that the proposed cumulative effects management cycle (Fig. 2) outlines the key foundations of effective policy in this era of rapid climate change. The state of systems and their impacts need to be assessed and then linked to policy with regionally defined thresholds and management triggers (Somers et al. 2018; Greaves et al. 2025). This should be translated into regional plans with legislative teeth to protect ecosystems from being pushed past thresholds by incremental decisions. As climate change shifts the baseline of environmental conditions, there is a need to mandate that regional cumulative effects assessment or other forward-looking policies include climate change vulnerability analyses.

By incorporating the preceding opportunities into a cohesive cumulative effects management cycle, there is potential to address the cumulative effects of climate change and local human activities. For instance, the Skeena Stewardship Assessment Forum (SSAF) exemplifies how Indigenous and Crown governments can collaborate on regional approaches that unite key elements such as on-the-ground monitoring, regional assessments, and spatial planning. The SSAF has published a regional assessment (SSAF 2021) of fish and fish habitat, which also incorporates a climate change vulnerability analysis (Price and Daust 2020). Results of this are now being incorporated into the co-managed Lakes Forest Landscape Plan (FLP). The Lakes FLP process is using this assessment to shape its direction, focusing on improved small stream management and addressing the cumulative effects of forest harvesting (Dunphy 2025). Additionally, efforts are underway to integrate cultural values into the assessment process, with the development of cultural indicators led by SSAF Nations. These indicators aim to reflect the cultural practices and knowledge of Indigenous communities, creating a more inclusive approach to resource planning and stewardship. While the implementation of these assessment-informed decisions is still in progress, the SSAF demonstrates a practical application of cumulative effects management.

Conclusions

In this paper, we have aimed to provide an integrative synthesis of the science and Crown governance of cumulative effects in salmon ecosystems of BC. We emphasize that this topic is extremely complex and built on challenges of environmental complexity, social conflicts, and a rapidly changing world—a so-called “wicked problem”. First, we illuminated that the salmon lifecycle is a journey through a multitude of stressors, jurisdictions, and laws. This integrative treatment of both the science and policy levers of cumulative effects revealed the sheer complexity of effective governance of salmon. Second, we examined a hypothetical model of cumulative effects and their governance that highlighted several barriers and opportunities. Whether through scarce monitoring, failure to assess impacts, lack of overarching limits, or isolated decision-making, the current management of human activities in salmon ecosystems appears to be enabling the progressive degradation of salmon habitats. In addition, the challenging reality is that managing multiple stressors will become even more difficult as any given human activity poses a cumulative effect to a backdrop of climate change impacts. While there is a prevalent inclination by Crown governments to manage to depletion and then expend high resources in uncertain recovery efforts (Lamb et al. 2023), we believe there is an urgent need to ask whether there is a different and better approach. For example, what is the portfolio of watershed stewardship approaches that would enable diverse realizations of thriving ecosystems for salmon and people?

Our synthesis revealed that there are many existing policy options within Crown governance that could improve the management of cumulative effects for salmon ecosystems. Many of these policies have rarely been used (e.g., temperature-sensitive stream designation). We also stress that the challenge of cumulative effects requires a holistic and interconnected policy framework, and it is not clear where that framework will come from—perhaps from the empowerment of regional co-governance agreements, the application of DRIPA (2019) to key policies, and the advancement of the WSA. We emphasize that the policy landscape in BC is rapidly changing. If society values salmon and all that they do for economies, environments, and cultures, the current challenges facing Pacific salmon underscore the urgent need for a paradigm shift, including transformative environmental policies that prioritize the well-being of salmon ecosystems and the communities that rely on them.

Acknowledgements

This paper arose from discussions related to the Watershed Futures Initiative, which aims to enhance the climate resilience of BC’s salmon watersheds by researching cumulative effects and sharing best stewardship practices. Sincere thanks to Bob Chamberlain, Emma Hodgson, and Sean Naman for their input in early conversations that shaped this perspective and to Trisha Hall for comments on an earlier draft. We thank Fuse Consulting who designed graphics used in Figs. 1 and 2. Funding for this work includes the BC Salmon Restoration and Innovation Fund (BCSRIF_2022_362), “Watershed Futures Initiative: Towards climate resilience of salmon watersheds”, as well as support from the National Science and Engineering Research Council of Canada, the Eugene Maughan AFS Scholarship, the Liber Ero Foundation, the Sitka Foundation, and Simon Fraser University.

Article information

Editor(s)

Andrea Olive, Jeff C Clements

History dates

Received: 4 February 2025
Accepted: 25 May 2025
Version of record online: 2 September 2025

Copyright

Data availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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Competing interests

The authors declare there are no competing interests.

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