

Assessing cumulative effects to support Indigenous-led ecosystem-based management in salmon watersheds

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Abstract

The management of cumulative effects from multiple pressures is a key challenge to achieving thriving watersheds for salmon and people. We documented and mapped cumulative effects across salmon watersheds of the Central Coast of what is now known as British Columbia, Canada, a region known for implementation of principles of ecosystem-based management and collaborative governance between Indigenous and Crown governments. Our approach is founded on the interests, knowledge, and values of Kitasoo Xai'xais, Nuxalk, and Wuikinuxv Nations. Working with Indigenous and non-Indigenous knowledge holders, we mapped over 30 pressures for salmon and other species important to salmon watersheds—temperate forest ecosystems subsidized by the annual return of salmon from the marine environment. We identified hotspots for cumulative pressures in major valleys including the Bella Coola, the Sheemahant, and the Kimsquit and demonstrate how single and multispecies approaches can change results. Hotspots of impact were contextualized with qualitative analysis and graphical illustrations describing complex changes to salmon including abundance, size, and behaviour and resulting impacts on people. Our work provides an example of how cumulative effects assessments that are underpinned by Indigenous values can shed light on knowledge gaps and opportunities for improving implementation of ecosystem-based management.

Key words: cumulative effects, salmon watersheds, ecosystem-based management, Indigenous

Introduction

Human activities can have variable and accumulating impacts to the persistence and function of species within ecological communities. Accounting for the variation in the intensity of human activities over space and time and their potential cumulative effect on the health of different, yet interconnected species is a methodologically challenging problem for the field of cumulative effects assessments (CEA) (Canter and Ross 2010; Duinker et al. 2013; Hodgson et al. 2019; Sutherland et al. 2022). Closely linked with the problem of understanding the effect of cumulative pressures on ecological systems are the complex challenges of determining which agencies or institutions have the jurisdiction, expertise, and capacity to prevent, mitigate, or manage cumulative pressures (Epstein et al. 2015). Responding to massive changes in ecological conditions that result from human activities requires institutions that can effectively govern and manage the pressures that are applied to species and resources and the services they provide (Cumming et al. 2020).

The ability of humans to effectively manage the consequences of cumulative effects on species and ecosystems is determined by the spatial and temporal scales at which their governing institutions can operate. Institutions may be too localized or too large to meaningfully address ecological problems in space and time, which can contribute to functional mismatches if connected elements of the ecosystem are managed independently (Folke et al. 2007; Epstein et al. 2015). Ecosystem-based management is one framework that has been suggested as a potential approach for remedying many of the issues related to managing cumulative effects. Acknowledging humans as part of the broader ecosystem and the interconnected nature of social, economic, and ecological goals is at the center of ecosystem-based management (Engler 2015; Long et al. 2015). This ethos is in contrast to colonial or “conventional” centralized management that attempts to shape human activities in a fragmented way by managing individual resources through distinct agencies with separate mandates (Costanza et al. 1998; Long et al. 2015).

Indigenous governance systems represent an example of spatially and temporally suitable institutions for implementing ecologically and socially responsive management. Indigenous governance systems are predicated on rights and responsibilities that precede colonization and align with ecosystem-based management through the development of laws and practices that have evolved in specific places over long periods (Turner et al. 2000; Trospen 2002), emphasize a deep connection between humans and their environment (Salmón 2000), and are sensitive to activities that threaten the sustainability and persistence of ecosystems (Turner and Clifton 2009).

A prominent location for the implementation of ecosystem-based management has been in the “Great Bear Rainforest” which covers much of the north and Central Coast of British Columbia, Canada. The region gained notoriety in the 1990s as global campaigns drew attention to unsustainable forestry practices leading to loss of old growth temperate rainforest, driven by technocratic decision making that limited public participation and neglected values beyond the forest industry (McGee et al. 2010). Through a novel and collaborative planning process, Environmental non-government organizations, forest industry representatives, title holders (i.e., Indigenous governments) and Crown governments agreed to employ principles of ecosystem-based management in commercial forestry, and find new ways to promote sustainable economic growth in communities across various economic sectors (Saarikoski et al. 2013). Ecosystem-based management within the region has been crafted around specific focal old growth forest dependent species, including grizzly (*Ursus arctos horribilis*) and black bear (*Ursus americanus*), mountain goat (*Oreamnos americanus*), black-tailed deer (*Odocoileus hemionus*), coastal tailed frog (*Ascaphus truei*), northern goshawk (*Accipiter gentilis*), and marbled murrelets (*Brachyramphus marmoratus*). The agreements around the Great Bear Rainforest are not a single document but represent an evolving negotiation process taking place within the context of continued Crown management and legal frameworks (Curran 2017).

Within this region, Pacific salmon (*Oncorhynchus* spp.) play a key role as a vector for nutrients moving from the marine into freshwater and surrounding terrestrial areas where they spawn (Cedarholm et al. 1999; Helfield and Naiman 2001; Hocking and Reynolds 2011) (Fig. 1). Prior to colonization and since time immemorial, Indigenous families, communities, and their Nations have sustainably managed the harvest and abundance of salmon (Trospen 2002; Atlas et al. 2021), but more broadly, the lands and waters of their territories via their own complex, “ecosystem-based management” frameworks that support reciprocity within the place (Brown and Brown 2009; Reid et al. 2022a, 2022b). Today, Indigenous Nations within the region continue to enact management that is based in Indigenous law while simultaneously collaborating with Crown governments on land and marine-use planning and management (Ban et al. 2019; Beveridge et al. 2020). The knowledge and practices of Indigenous communities offer valuable insights for addressing the impacts of historical land and resource use in the region, and Indigenous Nations are well-placed to assess cumulative effects (Ulaski et al. 2025).

Salmon are foundational for the cultures and economies of many coastal people in the Pacific Northwest. Against a backdrop of colonial fisheries management and the development of extractive industries and urban expansion on land, salmon on the coast of British Columbia and throughout the Pacific Northwest have declined (Gresh et al. 2000; Atlas et al. 2022; Peacock et al. 2023), with consequences for the ecosystems and people they support (Turner et al. 2013; Oke et al. 2020). Increasingly, researchers are calling for ecosystem-based management of Pacific salmon that considers their contribution to terrestrial habitats and the critical role they play in supporting ecosystem function (Darimont et al. 2010; Levi et al. 2012; Adams et al. 2021). This raises several key challenges including the estimation of cumulative effects in both marine and terrestrial habitats for salmon as well as the associated species that rely on them (Walsh et al. 2020; Adams et al. 2021).

Herein we address challenges for incorporating cumulative effects into ecosystem-based management of salmon and their habitats. The intentions of this paper are two-fold:

1. Identify and describe the range of anthropogenic pressures that are impacting salmon and the salmon forest within the Great Bear Rainforest region, characterize the impact of those pressures and document critiques to current and historical management practices; and
2. Map the spatial distribution of anthropogenic pressures and their interaction with the focal species of the salmon forest.

We link methods for inclusive regional-scale CEAs (Adams et al. 2023) with a qualitative analysis of the pressures and their effects to gain an understanding of salmon forests on the Central Coast of British Columbia, Canada. Through combining spatially explicit quantitative methods for mapping species, pressures, and their interactions, and with qualitative descriptions of the impacts of those pressures, we gain insight into the emerging patterns of human activities and ecology and how regional institutions might be improved to increase responsiveness to title holders and residents of the communities that call the Central Coast home.

Materials and methods

Regional context

The Central Coast region of British Columbia comprises an area that stretches along the coast of mainland British Columbia roughly between Vancouver Island and Haida Gwaii (Fig. 2). The region represents the combined traditional territories of the Kitasoo Xai'xais, Nuxalk, Heiltsuk, and Wuikinuxv Nations who have stewarded the lands and waters since time immemorial (note the full “Great Bear Rainforest” planning region encompasses additional traditional territories beyond those in the Central Coast) (Cannon and Yang 2006; Campbell and Butler 2010). Our research team collaborated with the staff from the Kitasoo Xai'xais, Nuxalk, and Wuikinuxv Nations within this area (hereafter “the Nations”) to build a CEA for focal species within their

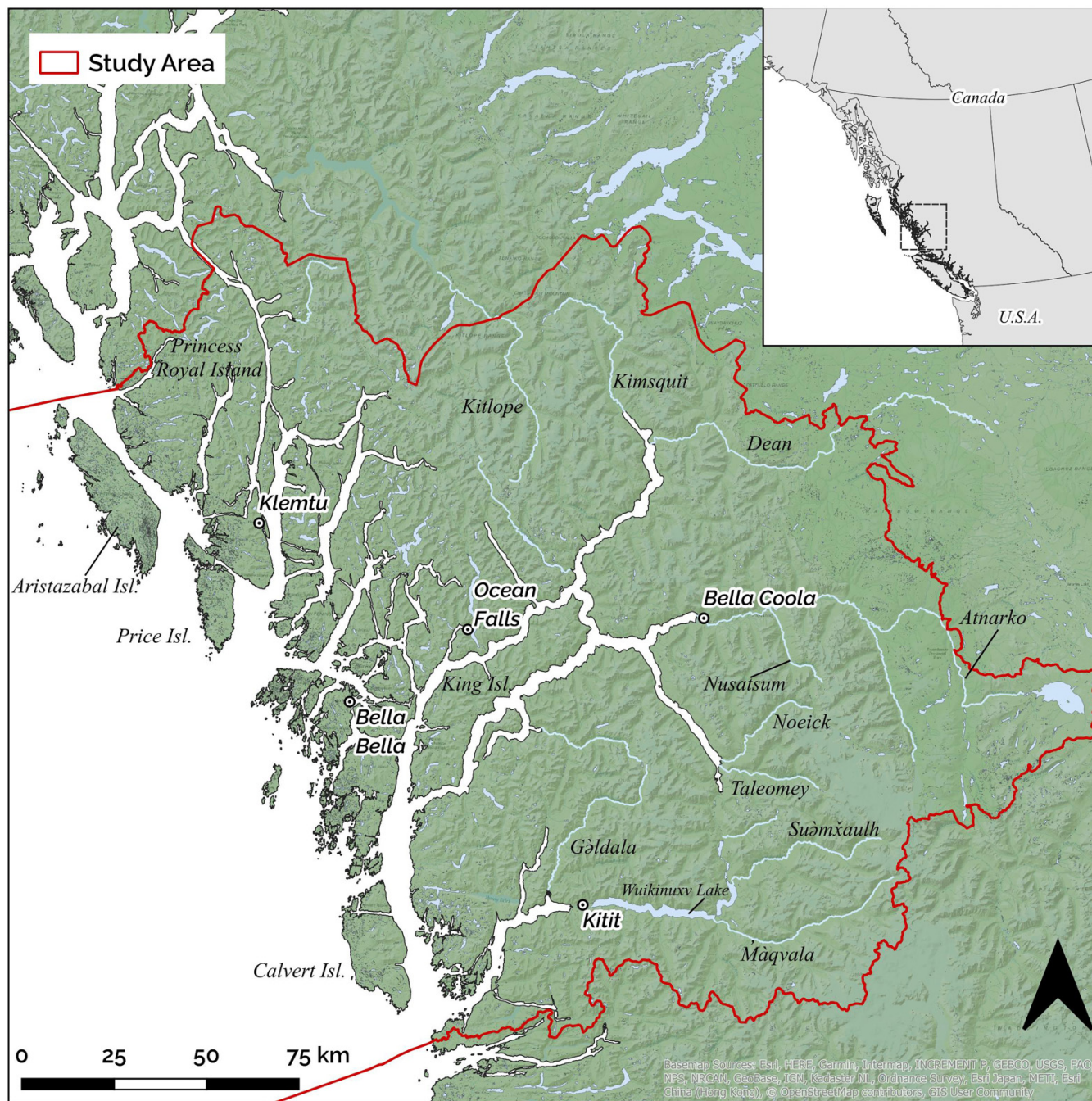
Fig. 1. The “Salmon Forest” within a watershed—illustrated by Briony Penn.



territories for inclusion into ongoing ecosystem-based management in the region (for more detail, see Adams et al. (2023) and Tulloch et al. (2024)). We respectfully note that the Heiltsuk Nation did not participate in this work. However, many of the quantitative datasets used span the broader Central Coast region; our spatial analysis reflects this wider geography. To ensure we honoured the voices and knowledge shared with us, our discussion highlights the priority areas identified by the Nations who participated, where our interview data most directly reflects community perspectives.

Salmon play a foundational role to the people, lands, and waters of the Central Coast, linking marine, and terrestrial ecosystems by contributing to regional food security and culture (Reid et al. 2022a) and sustaining relationships between humans and wildlife (Artelle et al. 2016). Six species of salmon including chum (*Oncorhynchus keta*), coho (*Oncorhynchus kisutch*), Chinook (*Oncorhynchus tshawytscha*), pink (*Oncorhynchus gorbuscha*), sockeye (*Oncorhynchus nerka*), and steelhead (*Oncorhynchus mykiss*) are supported across a variety of watersheds, representing a diverse suite of run-

Fig. 2. A map of the Central Coast region, with study area outlined in red (see the text below for Indigenous place names).



timing, genetic differentiation, and habitat uses (e.g., lake and river rearing sockeye, variations in run timing across a single river and species). The Central Coast remains a relative stronghold for salmon; however, many populations have experienced decline compared to their post-colonial historical abundance (Adams et al. 2021; Atlas et al. 2022; Reid et al. 2022b).

Elicitation of cumulative impacts

We identified pressures for salmon and other species occurring in the study region through a process of expert elicitation

grounded in the interests and values of the collaborating Nations (for a detailed description of our expert elicitation process, refer to Adams et al. 2023). Nation stewardship staff worked with our research team to select focal species (generally referred to as “valued ecosystem components” in the cumulative effects literature) to be included in the CEA—Pacific salmon (assessed as a group of *Oncorhynchus* species, including Chinook, coho, pink, chum, and sockeye), as well as old growth forest (assessed as the assemblage of tree species that constitute old growth in the region), grizzly bears, black bears, and marbled murrelets.

The focal species were then used to frame discussions with expert knowledge holders from Central Coast communities about the types, scale, and location of pressures and their impacts to focal species or their habitats since colonization (circa 1880s) throughout each Nation's lands and waters. We worked in small groups through semi-structured interviews and knowledge sharing workshops. We used a snowball approach to identify knowledge holders stemming from relationships held by our research team's previous experience in the region. Experts ranged from Indigenous knowledge holders to scientists to commercial fishermen or ecotourism guides; all who had expertise in any number of the focal species (Adams et al. 2023). In total, 53 individuals contributed their knowledge.

Visual guides such as maps and conceptual models were used to illustrate the relationships of identified pressures and focal species, while new spatial data layers were created by digitizing the shared information and amending existing data. Written and graphical notetaking recorded during elicitation sessions were used to assemble key themes from these discussions (Adams et al. 2023).

Identifying themes

While the elicitation phase was primarily intended to identify pressures and impacts to salmon and other focal species on the Central Coast, discussions were much broader ranging and included impacts for people, culture and economies, and coastal ecosystems at large. To reflect the holistic nature of the information that was shared, the graphical and written notes of the workshops and written comments from workshop participants were used to derive key themes that represent the fundamental concepts we heard from experts related to pressures that are facing salmon and the communities they support (Ryan and Bernard 2003).

Notes recording oral comments from each workshop and written feedback provided by workshop participants were combined and analyzed using a generalized inductive approach (Thomas 2006), wherein we summarized common themes from experts into broad categories of pressures, population health, and peoples' relationships to salmon. For pressures and population health, subtopics were identified that conveyed different elements of those themes. We selected key quotes that distilled themes and represented each of the participating Nations. After generating these categories, representatives from each Nation were asked to evaluate the findings to check for accuracy of the interpretations and to provide feedback.

Mapping cumulative impacts

Cumulative impacts of the identified pressures were mapped following well-established methods outlined in Halpern et al. (2008), by combining spatial information on species presence, the intensity of pressures, and vulnerability of each species to those pressures. First, spatial data describing the distribution and importance of the focal species habitats were collated and mapped to a 1 km² grid. An iterative process informed by local experts was used to identify rele-

vant datasets and confirm map accuracy. Depending on the nature of the data that was available, we used various methods to represent habitat importance for each species. In some cases, we rescaled an existing ranking to a value between 0 and 1 (e.g., grizzly bears); in others we combined multiple existing datasets and calculated proportional coverage (e.g., old growth). Regardless of method, all species habitat maps were rescaled between 0 and 1. Table S1 in the Supplementary Material describes the data used and conversion process for each focal species.

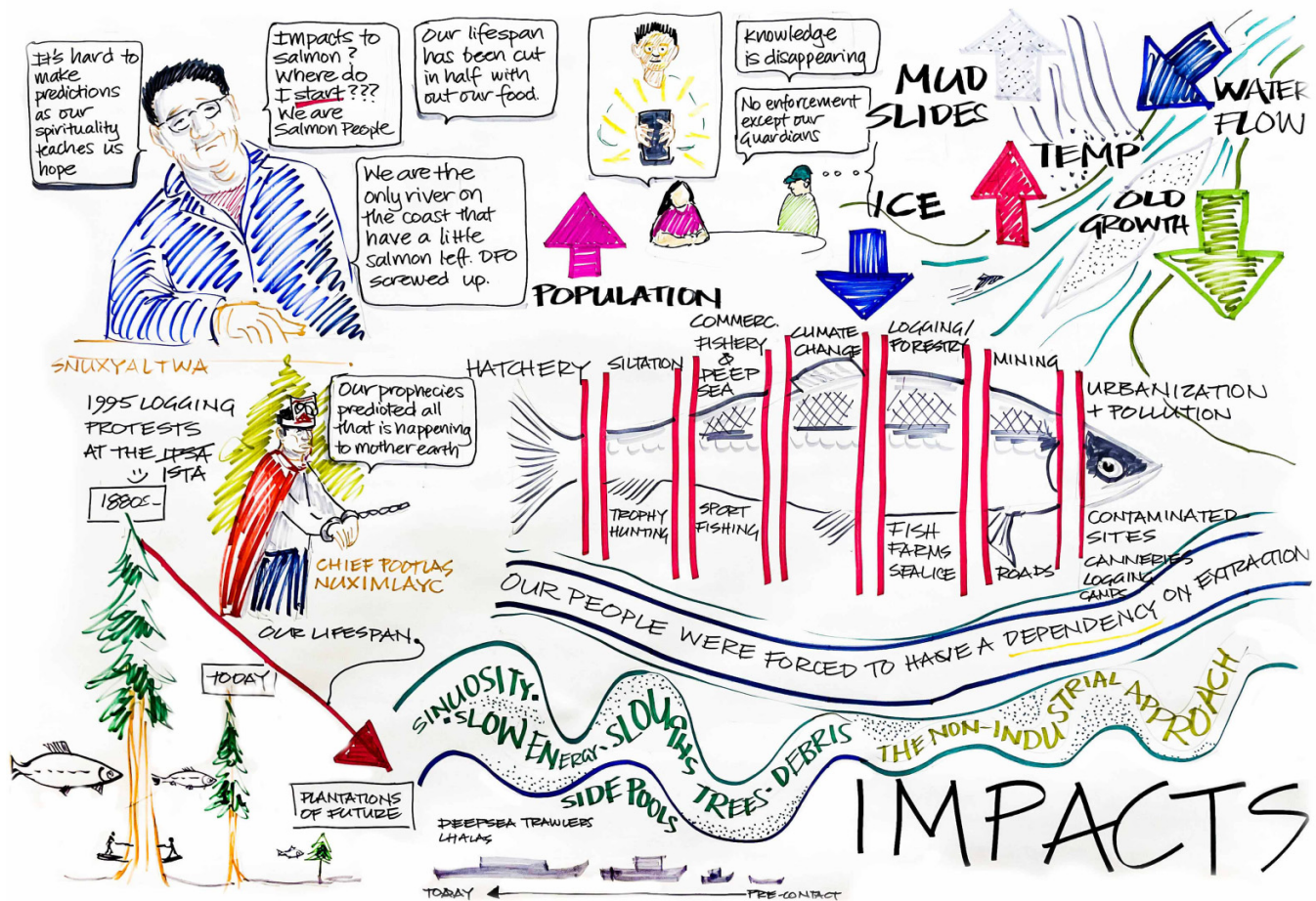
For the pressures we heard about from knowledge holders, we mapped those for which sufficient spatial data existed or could be created. Each pressure was mapped individually to the same 1 km² grid across the study region. Spatial datasets from a variety of sources were combined with the newly shared and digitized information from drawn maps provided by experts to characterize the distribution of each specific pressure. Pressure values were generated by various methods to be represented at the same scale. Some pressures were calculated as a density (e.g., roads or linear development), others a proportion of the grid cell that was covered (e.g., impervious surfaces) depending on the nature of the pressure and the data available. Table S2 describes how each pressure was calculated and represented in the grid, all pressure values were rescaled to values between 0 and 1 to put them on a unitless scale, allowing direct comparison.

Once pressures had been identified and mapped, experts on specific species were asked to score species' vulnerability to pressures from 1 to 6 (the sensitivity of each species to impacts from associated pressures), ranging from negligible to intolerable consequence for the focal species at the scale of individual pressures. Details for the elicitation of species vulnerability scores can be found in Tulloch et al. (2022). The vulnerability score was assumed continuous and rescaled to a value between 0 and 1 so that it was on the same scale as the pressure value and species habitat importance, and are listed in the Supplementary Material (Table S3). We conducted surveys among our experts for each of the focal species through emails, online conferences, and phone interviews. During the elicitations, we provided a spreadsheet detailing pressure type, with one row per activity, and asked experts to score or qualify the consequence variable for each species-pressure pair. The vulnerability of a species to singular pressures is difficult to study given the rarity of natural experiments; the assessment of vulnerability is primarily used to determine which pressures are relevant for which focal species, with some gradient for their relative severity. We modified the vulnerability values $\pm 20\%$ to account for uncertainty and analyze the effect on the overall impact score.

A cumulative impact score (I_C) for each 1 km² grid cell was calculated by multiplying the rescaled value of the prevalence (P) of each pressure (j) by the importance value of habitat (H) for each focal species (i), and the vulnerability (μ) value of each pressure-species combination.

$$I_C = \sum_{i=1}^n H_i * P_j * \mu_{i,j}$$

Fig. 3. Graphical notetaking image illustrating the impacts to salmon that were discussed during a workshop with Nuxalk Nation members and staff. Illustrated by Briony Penn.



With the total impact to each species mapped at a consistent spatial scale, resolution, and extent, the cumulative impact for the salmon forest was calculated by summing the values of spatially co-occurring grid cells.

The 1 km² grid species impact map for salmon and cumulative impact map for the salmon forest were summarized to the watershed scale using BC Freshwater Atlas assessments watersheds, which are a mesoscale hydrological unit with a target size ranging from 2000 to 10 000 ha in area (GeoBC 2022), and approximate a spatial scale for determining where to implement regional management actions (i.e., Service et al. 2018). The maximum impact score within each subwatershed was extracted to characterize the pressures acting on both salmon individually, and the salmon forest collectively within the hydrological unit.

Results

Cumulative impacts to salmon—themes from elicitation

Key themes that arose during discussions with experts about salmon returning to the Central Coast went beyond identifying a list of pressures that are impacting salmon and

the land–sea interface which they connect. These discussions were inexplicably linked with observations of the impacts of the pressures on salmon health, descriptions of spatial and temporal trends in salmon populations, phenology, and condition, and ideas for what is needed to restore stewardship for salmon in response to pressures and population trends. Each of these will be summarized in turn.

Pressures facing salmon

Experts identified a broad range of human activities that have had varying impact on salmon populations and their habitats since colonization (Fig. 3).

Freshwater habitat

Perhaps the most frequently mentioned threats to salmon were the historical and ongoing changes to freshwater habitats. There were a variety of human activities and pathways of effects mentioned in reference to changing freshwater habitats, but the most common causal factor was related to forestry practices. The recognition of the mediating effect of old growth forest on the characteristics of habitat quality was repeatedly brought up. Impacts to watershed net-

works of old growth forests from commercial logging practices have inhibited the forest's role in stabilizing salmon freshwater habitats via changed hydrological patterns due to the construction of roads and removal of trees and root networks, the loss of forest cover and riparian cover leading to warmer temperatures, and increased flooding rates and river heights that contribute to erosion, sedimentation throughout watersheds and into the creeks, and scouring events of the river bottom and salmon redds. Removal of large trees by harvest has also reduced the input of large woody debris into streams, diminishing structures used for predator avoidance, thermal refugia, and hydrological stability. Experts discussed historical logging practices without riparian buffers, where logging occurred up to and into creeks, which also contributed to mass and ongoing sedimentation and instability in salmon-bearing watersheds. Knowledge holders also identified that road building from valley bottom to the headwaters promotes increased vulnerabilities to landslides and flooding through improper drainage and transport of water from precipitation events, compounding the hydrological impacts of mass tree and riparian vegetation removal.

“Logged creeks are so much flashier. Since logging began in Wuikinuxv Lake [early 1960's], water rises faster and drops faster in the creek valleys that have lots of road logging in them. In September when the rains come and we're counting fish, we can count salmon in the creeks in the valleys with no roads even during a rainstorm - it takes 24 hours or more for one of these creeks to peak after peak rainfall. River valleys that were heavily logged are often peaking in flood height within a few hours of peak rainfall, flooding higher and then dropping more quickly than in the unlogged systems.” - Wuikinuxv knowledge holder.

Violent flooding makes it difficult for eggs or juvenile salmon to survive. Eggs can be washed away in scouring events, and species that rear in streams as juveniles can get stranded by mass flood events in side channels. Violent flooding impacts salmon at the spawning stage of their life cycle too; Wuikinuxv knowledge holders have noticed that extreme flood events in logged watersheds also make the water too fast for spawning in the runs that contain the gravel sizes preferred by sockeye, and the increased water velocity can directly scour redds right out of the gravel. Knowledge holders also identified that the increase in frequency and extremity of flood events and the associated erosion and aggradation in logged valleys causes the lower, most productive parts of those watersheds to shallow and spread out, straighten, increase velocity, and channelize, which then (a) increases stream temperatures, and (b) increases opportunities for predation due to lack of cover and generally shallower water, and (c) prevents adult spawner migration during the frequent late summer and early fall droughts. Knowledge holders also describe the heavily road-logged and tree-farmed watersheds as having generally lower flows in late summer than the unlogged watersheds.

In addition to watershed-scale logging impacts, the loss of pools in smaller creeks due to “creek clearing” (a historic practice of Fisheries and Oceans Canada, commonly referred to as the Department of Fisheries and Oceans (DFO) wherein large woody debris was removed) was often brought up by

older experts who attributed significant losses in returning salmon following years of creek clearing.

Finally, knowledge holders also identified that salmon habitat in roaded river valleys has been altered due to the armouring of river banks with large stones (e.g., rip rap) to stabilize banks near bridges, agriculture, or private homes. Armouring increases the speed of the river, prevents flooding into side channels, which are less favourable conditions for juvenile salmon survival or adult salmon migration.

“The river is the big piece we are overlooking: the sinuosity has changed, the speed of the river has increased – same amount of water has to get through half as much land. In the past flood season was like a big tide – not rushing like today.” – Nuxalk knowledge holder

Collectively, experts identified how pressures have resulted in rivers that support less salmon. The loss of large woody debris, and the simplification of channel structure have made rivers and creeks more prone to flooding and therefore egg scouring; sedimentation, aggradation, and loss of spawning habitat. The loss of over story riparian cover has resulted in warmer rivers leading to pre-spawn mortality and reduced food for juveniles. Other specific pressures related to pollutants and logging were also mentioned frequently, including contaminants from logging activity leaching into streams or accounts of trucks being driven directly through creeks with salmon in them.

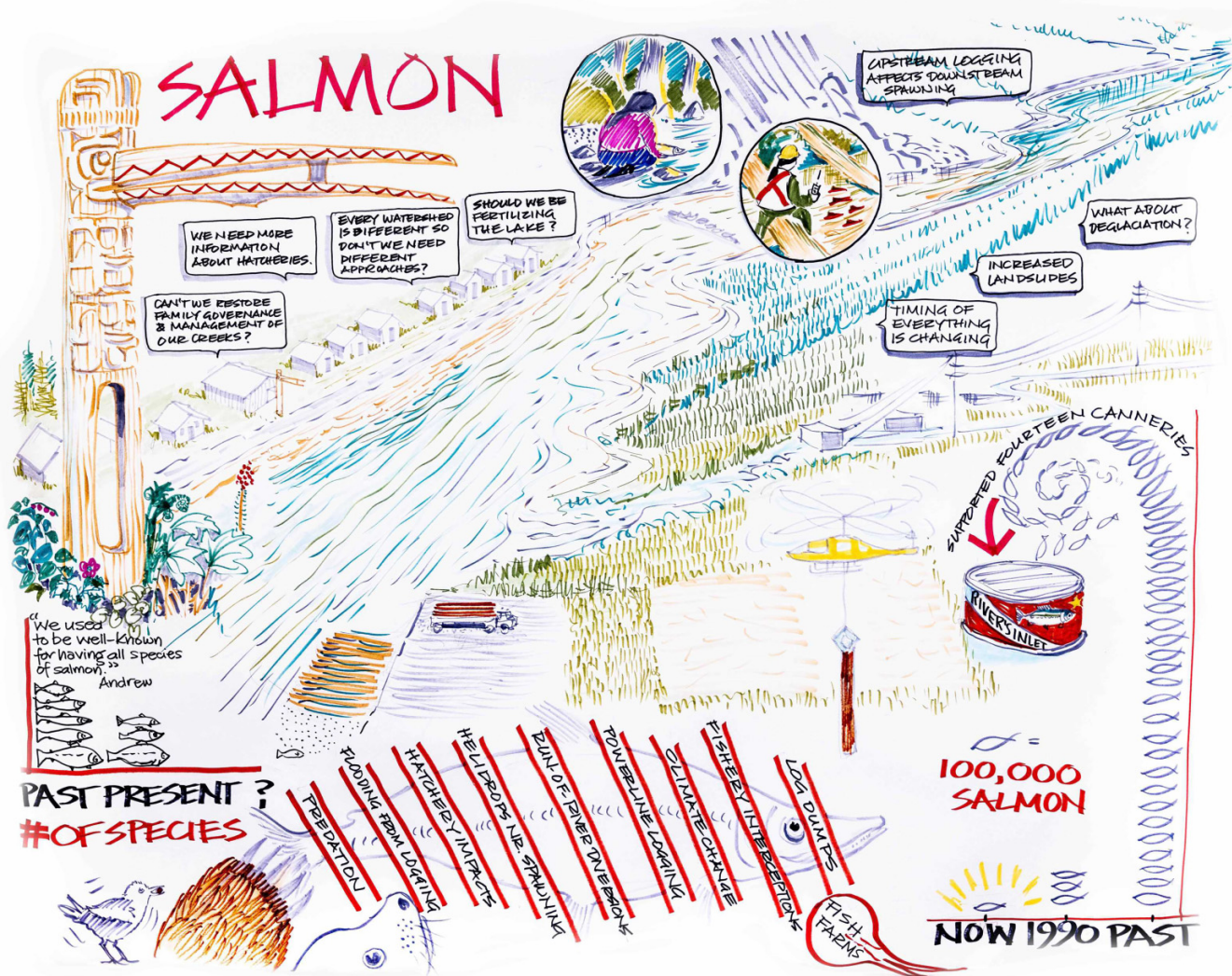
Fisheries

The management of the commercial salmon fishery was mentioned by experts with a similar frequency to the degradation of freshwater habitat as a strong pressure which salmon have faced since colonization. Commercial mixed stock fishing for canneries began in the late 1800s, followed by increased mechanization and capacity of commercial gillnet, troll, and seine salmon fisheries. However, the impact of fisheries was generally referred to in more explicitly temporal terms. Historical fishing practices were often used to illustrate the change in abundance that has occurred for salmon on the Central Coast. The amount of time that fisheries were open, as a proxy for historic abundance of catch, was a common figure cited to illustrate this change.

“Commercial fleet used to be open 6 days a week, then it was 5, then it was 3, then it was only for a few hours within a single day. That's a huge change in abundance of fishable fish – that's over 30 years. One generation.” – Nuxalk knowledge holder

Even while it was clear that abundance was in decline, experts pointed to federally-regulated fisheries remaining open year after year, resulting in collapse and the lack of available fishery today. Traditionally managed in-river (terminal) salmon fisheries were made illegal in British Columbia under the Fisheries Act in 1877 (Harris 2001; Atlas et al. 2021). The common assertion of the experts we worked with is that the commercial fisheries and canneries are primarily responsible for this collapse, and this irresponsibility is perpetuated today by the continued mismanagement by DFO (Fig. 4). The techniques and technology used for commercial fishing were also mentioned as sources of contemporary pressures on salmon, wherein sounding technology or gear make it

Fig. 4. Graphical notetaking image illustrating some of the impacts to salmon, and the decline in abundance of individuals and species that were discussed in a workshop with Wuikinuxv Nation members and staff. Illustrated by Briony Penn.



difficult for salmon to escape being caught. Experts alluded to fears of continued industrial harvest outside of Central Coast waters (i.e., Alaska and international fleets) in spite of local domestic fisheries being in a state of collapse.

The impact of recreational fisheries, supported by tourism, was also recognized as a threat. Tourism visits and vessel density increases in the region were cited by knowledge holders. Concerns were raised about impacts of catch and release for vulnerability to marine predation for Chinook and coho salmon. Knowledge holders also raised concerns about fresh-water recreational fishing where tourists are targeting fish close to their spawning grounds.

Predator-prey relationships

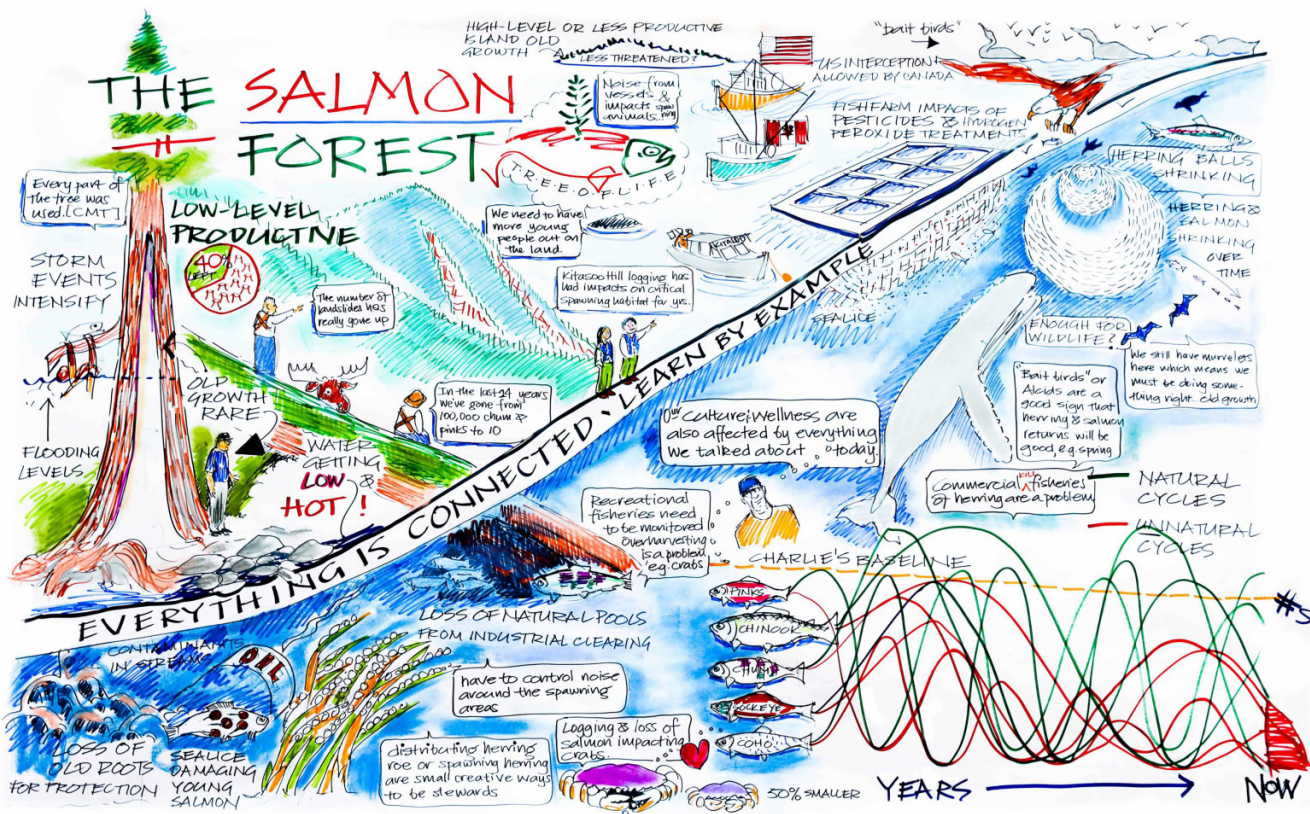
Experts emphasized a change in the abundance of other species that rely on salmon as a food source, and that salmon themselves rely on. Comments particularly focused on the increases in Pacific harbor seals (*Phoca vitulina ssp. richardii*). Seals were repeatedly identified as a problem due to their consumption of salmon. Knowledge holders noted

the remnants of logging infrastructure in the estuaries of logged valleys promoting seal density; abandoned boom logs can create good haulouts for seals at the mouths of rivers and creeks. The imbalance of a growing seal population in relation to salmon was amplified by other comments that mentioned the loss of eulachon (*Thaleichthys pacificus*) or Pacific herring (*Clupea pallasii*) as a food source for salmon.

Salmon aquaculture

The presence of salmon aquaculture and the associated risks of disease and parasite transmission was mentioned at a similar frequency to issues related predator-prey imbalances and represents further changes to the marine environment that poses risks particularly to juvenile salmon as they migrate out to the ocean (Fig. 5). Importantly, many pressures are focused on impacts to adult salmon, whereas references to salmon aquaculture were always in relationship to juvenile salmon and early marine survival.

Fig. 5. Graphical notetaking image illustrating connections of the salmon forest, relationships to the land, and trends in salmon abundance that were discussed during a workshop with Kitsoo Xai'xais Nation members and staff. Illustrated by Briony Penn.



Climate change

Many of the pressures that were described by experts to be impacting salmon were accompanied and contextualized by climate change. The impacts of changing climate were widely observed and understood by experts to be an important contributing factor to the health of salmon, and as a pressure that interacted with the others while also having direct effects. This was particularly true for pressures impacting freshwater habitats. The loss of the mediating effect of snowpack and glaciers at higher elevations on both the levels of water in streams and the temperature of water was a key concern. Salmon dying before they can spawn or being unable to access habitat due to thermal stress are consequences of loss of snowpack and glaciers or change in summer and early fall precipitation patterns (depending on the expert and their territory, wherein some systems are glacial-fed whereas others are bog or lake-fed). These climate impacts are compounded by the hydrological changes to salmon watersheds from deforestation mentioned above. General stochasticity or instability was another threat described by experts and attributed to a changing climate—the idea that systems are constantly dealing with either a drought or a flood was a consequence unique to the freshwater habitats required by salmon. Several comments also pointed to impacts of climate change on the marine environment including warmer temperatures at sea, anoxia impacting salmon

directly or through the food chain, and ocean acidification from increased atmospheric carbon. Finally, multiple comments linked a changing climate directly to the changing patterns of behaviour in salmon in terms of their emergence patterns and migration routes and the phenology of their freshwater or marine foods.

Salmon population dynamics

The discussion of the pressures facing salmon were inseparable from discussions of the impacts of those pressures on population dynamics. The concerns expressed by knowledge holders including disease transmission, the collapse of commercial fisheries in the region, the peak of commercial logging, and the expansion of salmon farming all culminating in the early 2000s. There were a number of changes in the health of salmon that were highlighted by experts in recent decades, and general agreement on the trends that have been observed. Primary trends that were expressed related to the overall population sizes, the sizes and health of individual fish, and the spatiotemporal habits of migration.

Abundance

In terms of population, there was near-universal agreement that the numbers of salmon (all species) returning had experienced a drop of orders of magnitude (Fig. 6). Some de-

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Fig. 6. Graphical notetaking image illustrating the disappearance of salmon species discussed in the workshop with Nuxalk Nation members and staff. Illustrated by Briony Penn.



scribed numbers of spawners in the creeks changing from thousands to tens, others described the abundance visually, how the river used to be “black” with returning salmon. There were some comments that mentioned the trend for some salmon species was increasing moving into the future; however, this was a minority opinion.

Knowledge holders mentioned many specific watersheds and the loss of salmon populations that they have experienced. For example, Wuikinuxv knowledge holders shared that the chum in the head of the Imaiq (Moses) River were all fished out after years of overexploitation and a single large seine opening, chum in the Gə`ldala (Kilbella) River were minimal by the mid 1980s due to habitat destruction caused by logging, coho used to be at the mouth of ččə`n (Drainey Inlet) and the Gə`ldala River but are no longer found in abundance, and that Wuikinuxv Lake sockeye are fewer, much smaller, and arriving in more consolidated bursts.

Size and condition

Experts also unanimously noted a general decrease in the size of individuals over the last few decades. Some experts reference necessary changes in fishing gear that have been made to accommodate that change, such as an half-inch decrease in net size. Chum, sockeye, and Chinook salmon were emphasized particularly for this drop in size. Experts also noted

decreasing condition of adult fish caught in both marine and freshwater food fisheries. For example, white spots on the flesh and rotting fins were reported for sockeye, an indication of an increase in stress related fungal infections (i.e., Neish 1977). Creek walkers in Wuikinuxv territory are also noticing the rise of jack (young male) sockeye in many of the systems they count fish in, at relative abundances much higher than previously noted.

Behaviour

While the numbers, size, and condition of salmon were generally agreed to be in decline, a further change was often cited related to the behaviour of the fish that remain, such as juvenile emergence or adult return timings. There were comments concerned with increased marine temperatures causing a mismatch between available food sources for juveniles. While knowledge holders are not directly observing juvenile salmon feeding, knowledge holders are observing shifts in the phenology of indicators (plants, weather, migratory species presence) that previously predictably linked to the arrival of food fish for salmon (e.g., herring), the emergence of fry, or the success of a salmon return. Combined with increasing information from research in the region on the mismatch of ocean foods and salmon migration (Tommasi et al. 2013), there is general concern about how climate change

and subsequent phenological shifts are affecting salmon survival. For example, if juveniles are emerging at a similar time as they have historically, but marine organisms responding to warmer temperatures occur earlier, this could result in a deficit in food available at a critical time for survival.

For adults, there were repeated references to a temporal consolidation of returning salmon that is occurring across different species where run timing is truncating.

“Fish used to come in stages: first nice big green ones, then the blue ones, then you knew you were getting to the end with the stubby nosed sockeye, followed by humpies. Now they all come at once. The last two or three years of fisheries [e.g., 2017 onwards] all the types of fish were coming at once.” – Wuikinuxv knowledge holder

The temporal consolidation was accompanied by further observations related to the impact across different habitats. In particular, smaller creeks were often cited as having a greater drop in abundance than larger rivers, where population decline was more marked in smaller systems. Knowledge holders postulated that smaller systems might be more vulnerable to habitat impacts from logging than larger watersheds, which may also be compounded by disproportionate effects of mixed stock fisheries on smaller populations than larger ones.

Relationships to salmon

Salmon and Indigenous people have coexisted on the Central Coast since the recession of the Cordilleran ice sheet. The health of the people and the health of salmon cannot be separated. Knowledge holders reiterated that the importance of our relationships to the places we live and depend on, the responsibility that we accept as stewards, and the forms of governance that facilitate these relationships were inseparable from the discussions of pressures facing salmon, and the impacts of those pressures. An ethic of care and reciprocity for the environment was repeated as an essential component that was missing from current Crown governance of salmon and their watersheds.

Historical regimes of management described a familial responsibility to individual creeks and watersheds, ensuring that each system was clean and cared for was a primary mechanism for maintaining abundant salmon. The regulations on freshwater and marine fisheries, as well as the criminalization of Indigenous stewardship practices in salmon watersheds, implemented by DFO, were recognized to have directed the decline of salmon, and without this food source, Nations were being driven towards dependence on the Federal Government.

“River cleaning – used to have lots of salmon. Everyone had a spot where they had to do creek cleaning – they cared for the creek, DFO stopped that.” – Nuxalk knowledge holder

“Last couple years have hunted but not able to shoot anything - moose and deer. Our youth not learning this valuable knowledge. I feel we’re going to have a bunch of future leaders that will not know what we know. It scares the life out of me.” – Nuxalk knowledge holder

The weakening of salmon populations due to external policy enforced by DFO that results in the loss of independence echoes more overt colonial policies aimed at assimilation and cultural genocide such as divide and conquer policies (Fig. 7). This history contributes to a tense relationship between the Nations and DFO (efforts to re-write this relationship are being explored through current reconciliation agreements for collaborative governance). The demand for salmon, and other resources of the salmon forest from international markets and expanding human populations were acknowledged as potential drivers and challenges to overcome. There was interest in returning to more traditional forms of governance and management of salmon and salmon habitat. This included more hereditary systems of leadership, increased monitoring of fisheries and habitats, and spending dedicated time in watersheds. There was heavy focus on habitat restoration from the majority of workshop participants, with emphasis on stabilizing rivers from the impacts of historic logging practices and providing thermal relief to creeks. There was also general encouragement of hatcheries as a piece to the solution and ensuring access to salmon. Several comments mentioned that most of the chum that are currently caught are from hatcheries. There was some concern about long term impacts of hatcheries on population health and desires for more research on the subject.

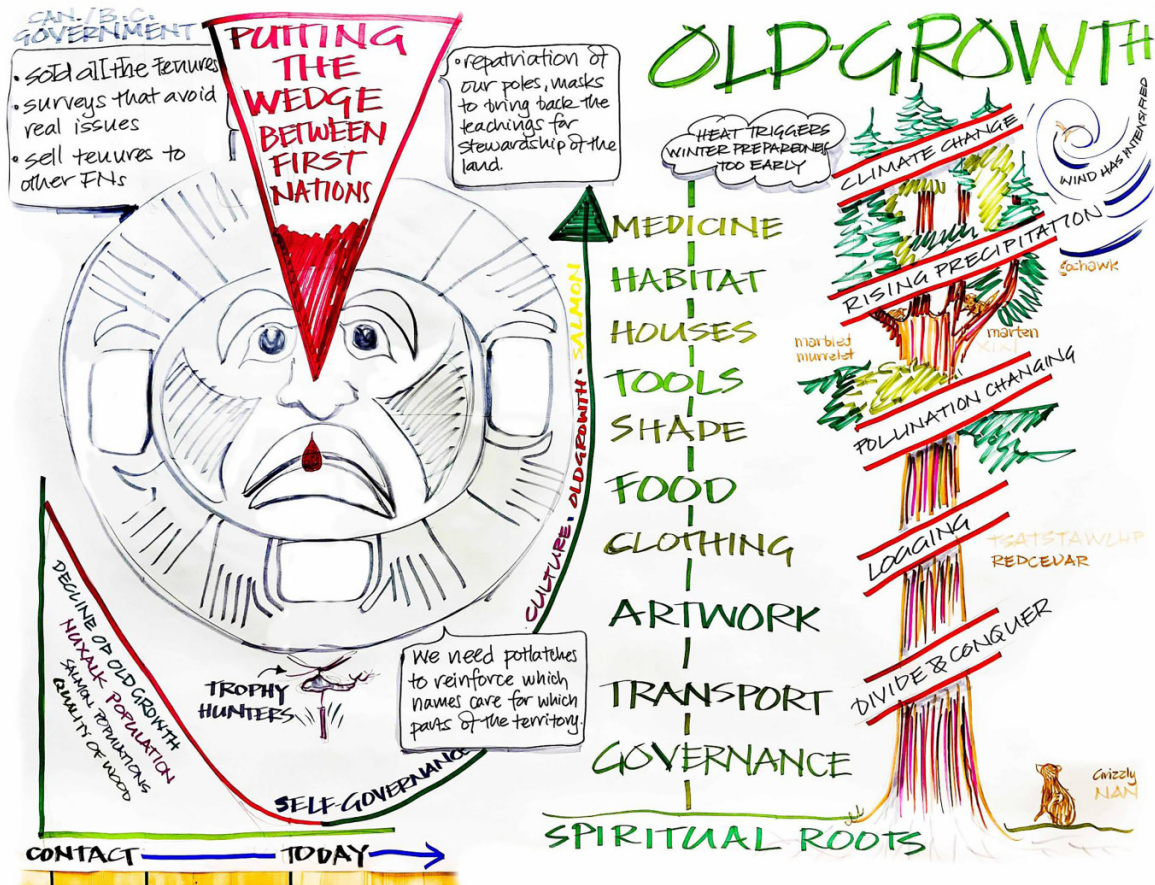
Spatial distribution of pressures

Using spatial distributions of pressures knowledge holders identified, we built impact maps for focal species in salmon watersheds (salmon, old growth, grizzly bear, black bear, marbled murrelet). Kernel density plots of the impact scores illustrate the spread of threat levels that each focal species faces across its habitat (Fig. 8). Impact score values closer to zero show the extent to which a given focal species may have access to refuge from the pressures mapped in this study. Importantly, salmon are shown to have very little habitat below an impact score of one (Fig. 8), indicating there are few freshwater habitats that salmon rely on throughout the Central Coast that remain relatively free from anthropogenic pressures.

We mapped the cumulative impact score for watersheds containing salmon habitat (Fig. 9), along with watersheds that contain all species of the salmon forest to illustrate where more systemic vulnerabilities exist and to inform management practices that may reduce and mitigate the risks posed by those pressures. The Bella Coola Valley had among the highest numbers of co-occurring pressures (see Fig. 2 for location labels). Watersheds that were close to the estuary of Kimsquit River and those immediately upstream of Wuikinuxv Lake in the lower reaches of the M̓a`qvala (Machmell) River also had among the highest co-occurring pressures for salmon. Areas closer to the coast on the southern end of King Island, and islands off the coast hold fewer threats to salmon.

The distribution of threats for salmon-dependent species was slightly different than salmon alone. The key hotspots for cumulative impacts among all species of the salmon forest occurred again in the Bella Coola Valley. Other locations that had high cumulative impacts include the lower reaches of the

Fig. 7. Graphical notetaking image illustrating the divide and conquer policies of colonial governments and the resulting cumulative impacts to old growth forests and salmon populations as discussed during a workshop with Nuxalk Nation members and staff. Illustrated by Briony Penn.



Kimsquit River in the north, the watersheds in the vicinity of Ocean Falls in the central region of the study area, and the Gəldala watershed. In the southern portion of the study area upstream of Wuikinuxv Lake, the upper reaches of the Suəmx`aulh (Sheemahant) River have higher threats across the salmon forest relative to the Mə`qvala River.

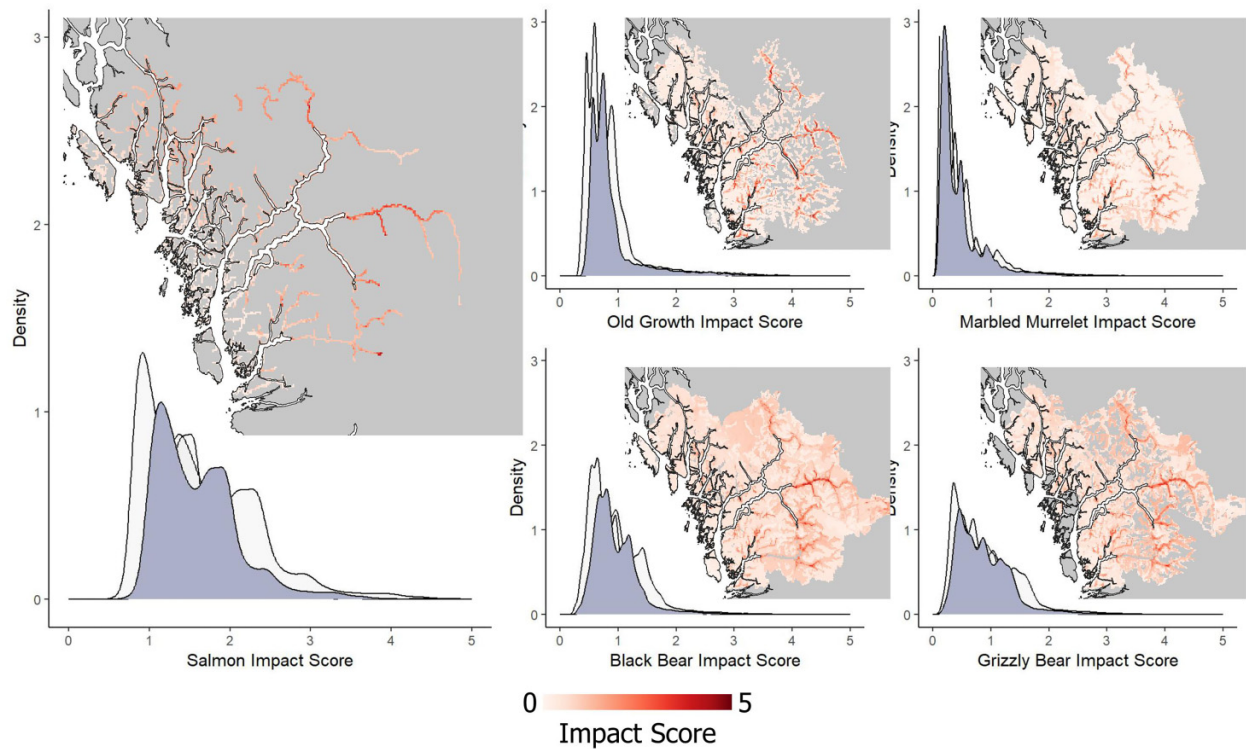
Discussion

The effective implementation of ecosystem-based management relies on the recognition of local values and knowledge regarding ecological conditions and resources, and how the governing institutions reflect the needs, values, and interests of communities (Ebbin 2002; DeCaro and Stokes 2013). Knowledge holders from the communities on the Central Coast identified current and historical pressures acting on salmon and salmon ecosystems, related to fisheries, climate change, forestry, tourism, energy development, salmon aquaculture, and the changing food web dynamics for salmon and other species of the salmon forest. These pressures were understood to be causing a range of impacts on the health of the species, including an order-of-magnitude decline in abundance, changing spatiotemporal patterns in behaviour, and the health and size of individual fish. Those impacts to

salmon propagate through to the relationships that communities have with salmon and their ability to steward them effectively.

Some of the impacts of pressures to salmon health that we heard from experts in community have already been reported in the scientific literature, much of which has been co-produced by members of the Wuikinuxv, Nuxalk, Kitsoo Xai`xais, and Heiltsuk First Nations. Reid et al. (2022b), describe abundance declines that average 91% for sockeye, 78% for pink (odd and even year combined), and 58% for chum from a baseline period of 1960–1990 compared to 2015–2020. Adams et al. (2021) estimate a 94% decline in the equilibrium population size for sockeye in the Wuikinuxv Lake system after a collapse in the mid 1990s, and Atlas et al. (2022) estimates a decline in chum salmon of 90% since 1960 across the Central Coast. Declines in the size of fish have been reported throughout the Pacific Northwest, as well as the resulting impact to both the fecundity of individuals, and their ability to provide ecosystem services, for coastal watersheds and communities (Oke et al. 2020; Malick et al. 2023). Research into the impacts of commercial logging practices on high and low flow events in salmon watersheds also corroborate assertions of knowledge holders in our work (e.g., Segura et al. 2020).

Fig. 8. Impact score kernel densities for each focal species. Higher impact scores indicate greater threat levels, the density represents the number of pixels (area) at that impact score. The associated raster accompanies each plot for context. Light grey densities indicate $\pm 20\%$ adjustments to the vulnerability value applied to each pressure species combination.



The cumulative aspects of declining salmon health can make it difficult to identify drivers of decline and their impact on salmon health or abundance. In our study, we heard that salmon were migrating to rivers at more similar times and that smaller creeks had disproportionate impacts. There is evidence that Bella Coola chum are comprising an increasing share of the overall chum population on the Central Coast (Atlas et al. 2022) and experts described a truncation of run timing in Central Coast systems across species and territories. In addition to this, monitoring effort over time has degraded and biased toward larger rivers (Price et al. 2008; Atkinson et al. 2025). The confluence of hatchery production, the distribution of monitoring effort, and the variation in the impact of cumulative pressures across scales complicate how we might interpret our cumulative impact map.

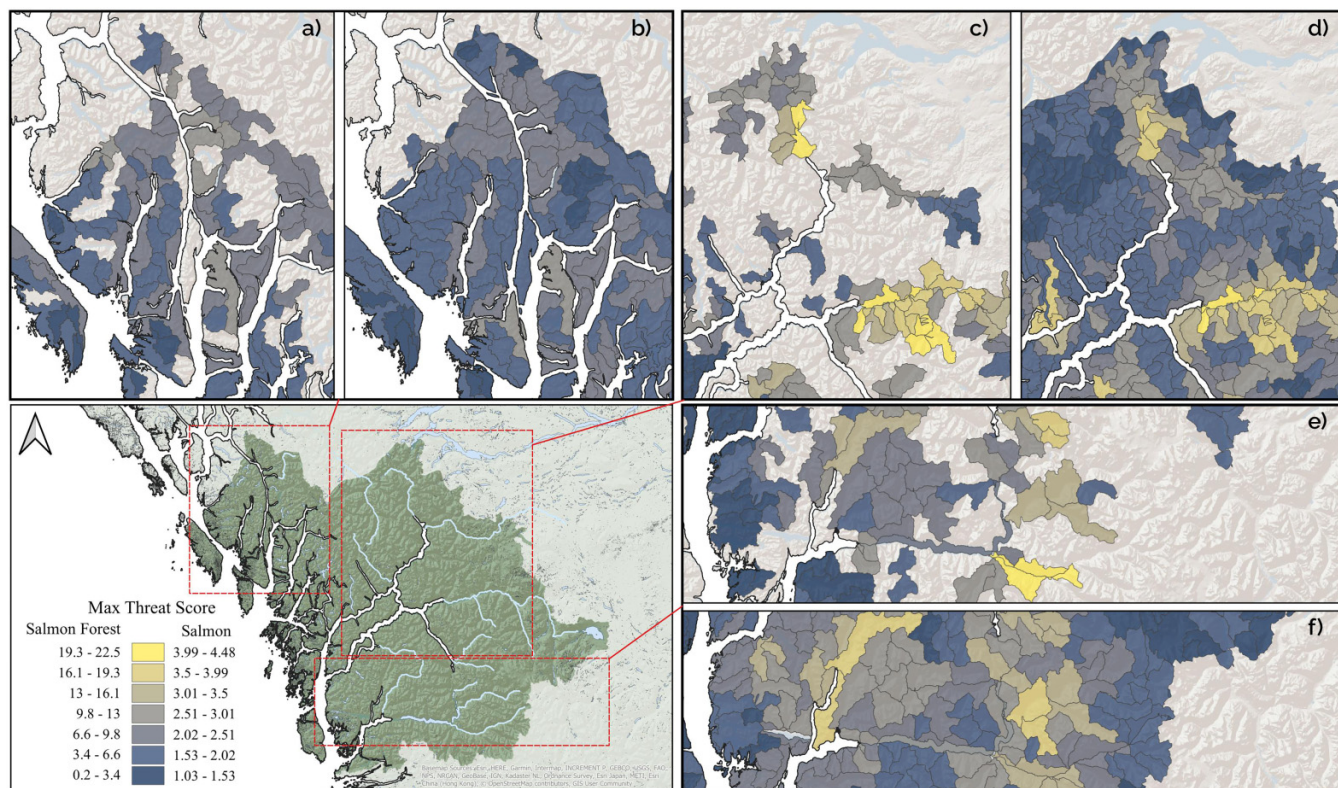
Mapping over 30 pressures summarizing cumulative effects by subwatershed revealed hotspots in several river valleys (Fig. 9). The focus of human activities in these larger river valleys, together with the potential erosion of salmon spatio-temporal diversity, creates a concern for negative feedbacks where salmon increasingly concentrate in places where pressures are both greater, and more difficult to manage. Phenological diversity plays an important role in the evolutionary resilience of populations (Sgrò et al. 2011) and for species that depend on the nutrients salmon bring into terrestrial systems (Schindler et al. 2013). By mapping pressures and contextualizing those results with qualitative expert knowledge of what is happening on the ground for health and behaviour of salmon populations we gain insight into how the system

is functioning as a whole. The interacting factors of salmon health should be considered in future studies that attempt to link drivers of decline to impacts on salmon populations and the phenological shifts in adult migration should be further investigated (Tillotson et al. 2021).

We also compared a single-species focused cumulative pressure map to one that considers multiple species of the salmon forest. We found that hotspots for cumulative pressures were largely similar, but did differ in particular contexts. For example, in the southern portion of the study area, in the tributaries upstream of Wuikinuxv Lake, pressures for salmon were highest in the Ma`qvala River valley; however, after considering pressures to old growth forest, bears, and marbled murrelets, the Su`mx`aulh River became the most highly impacted region. This underlines the importance of trade-offs when selecting focal species for assessment (Lindenmayer et al. 2007). While a single species approach might provide more insight into the specific mechanisms underlying the threat and suggest actions for recovery, an approach that considers multiple, interlinked species exposes the siloed approaches to resource management that has enabled multiple impacts to accumulate over space and time (Hodgson et al. 2019).

We did not consider the relative impact of different actions that can be taken to remove or mitigate pressures and their impacts on the salmon forest, or their cost effectiveness (Tulloch et al. 2015; Walsh et al. 2020). Although a large number of individual pressures may be alleviated in certain areas, the actions required could range from implementing habitat restoration, to road deactivation, to policy

Fig. 9. Impact maps for watersheds throughout the study area. Panels (a), (c), and (e) display the max threat score for salmon in watersheds that directly contain salmon habitat, while panels (b), (d), and (f) show max threat scores for all species in the salmon forest cumulatively.



levers like issuing Recreation Orders under Section 58 of the Forests and Range Practices Act, which allow the Ministry of Environment and Climate Change Strategy to order the restriction or prohibition of recreation uses on Crown land. The effectiveness of these strategies to improve the health of salmon and the salmon forest can vary along with their physical and social feasibility, and should be considered within a conservation decision framework (Carwardine et al. 2019; Tulloch et al. 2020; Walsh et al. 2020; Hemming et al. 2022).

The interaction and additive assumptions of pressures and the impact to the focal species is an understood weakness of mapping approaches to cumulative assessments, because they may not accurately capture the complex reality of how multiple stressors affect an ecosystem (Hodgson et al. 2019). However, incorporating Indigenous expert knowledge on species interactions is a key step forward for cumulative impact assessments. Our maps characterize the types of threats that are acting across the landscape and inform broader strategies that may need to be taken to protect and maintain the health of focal species. The cumulative pressure maps are contextualized by the repeated mention and theme of relationships and management for salmon. The reciprocal relationship with place that is expressed in many Indigenous cultures is eroded through the deterioration of salmon populations and the habitats they depend on. Several comments addressed the connection to the land as a defining character of identity:

“We need jobs and we need to remember who we are, to go harvest, and to be well!” - Kitsoo Xai'xais knowledge holder

“Harvest is ceremony. The land is our classroom. When we can't harvest, we can't pass on our teachings” - Kitsoo Xai'xais knowledge holder

“The colony is one of the biggest issues - mismanagement by DFO – taking our food and forcing us to be reliant on the colony. Taking our fish and our trees and then minerals and then oil and gas, need to put a stop to it now.” - Nuxalk knowledge holder

The solutions proposed for salmon watersheds throughout our discussions with experts included a heavy emphasis on moving away from economic dependence on centralized crown management overseeing resource extraction economies, and moving instead towards freshwater habitat restoration and a return to traditional family- or clanded management practices within their Nation's governance systems. Indeed, many coastal Nations are currently investing in nonextractive economies, while simultaneously investing in cultural and habitat restoration works in their watersheds. Decentralization of management and robust collaborative frameworks are both key elements for ecosystem-based management that mirrors the hierarchical structure of the ecosystems themselves (Engler 2015). There has been increasing recognition of Indigenous jurisdiction across the state of Canada; an increasing number of court cases have affirmed Indigenous rights and title (Artelle et al. 2019). In the

Central Coast region, collaborative governance and reconciliation agreements for both terrestrial and marine environments are also emerging, bringing together Indigenous and Crown approaches to governing. For example, the Great Bear Rainforest Land Use Order ([Province of British Columbia and Ministry of Forest Lands and Natural Resource Operations 2016](#)), and the Fisheries Resource Reconciliation Agreement ([CFN 2017](#)). With the goal of revitalizing local fishing and including Indigenous perspectives in the management process, the Fisheries Resource Reconciliation Agreement is creating a process for Nations to collaboratively manage specific species with the Department of Fisheries and Oceans ([CFN 2017](#)). Despite this progress Indigenous Peoples continue to be under-represented in resource stewardship decision making process ([Arsenault et al. 2018](#); [Daigle 2018](#)).

Conclusion

This work examines historical and present-day cumulative pressures impacting salmon watersheds on the Central Coast of British Columbia. There remain a number of challenges for salmon watersheds including a lack of recognition for natural resource management systems based in Indigenous legal principles, differences in values between colonial and Indigenous environmental governance, narrow spatial definitions for the assessment of adverse effects, and the exclusion of species interactions in CEAs ([Connors 2023](#)). Incorporating an ethic of care in decision-making processes informed by the resurgence of Indigenous law, along with advancements in data collection and methods for mapping and assessing cumulative effects are both important steps for improving the resilience of salmon watersheds moving forward.

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Data availability

Indigenous Peoples have fundamental rights over data related to their communities, traditional knowledge, cultural practices, and territories. This includes the rights to ownership, control, access, and possession of such data. Our research adheres to the CARE principles (Collective Benefit, Authority to Control, Responsibility and Ethics), as outlined by [Carroll et al. \(2020\)](#). These principles emphasize Indigenous self-determination and safeguard Indigenous knowledge, cultures, and intellectual property. While Tables S1 and S2 contain publicly accessible data sources, we have deliberately excluded any proprietary Indigenous data to respect these rights.

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Competing interests

All authors have no competing interests to declare.

Supplementary material

Supplementary data are available with the article at <https://doi.org/10.1139/facets-2025-0082>.

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