Cumulative Effects of Threats on At-Risk Species Habitat in the Fraser Valley, British Columbia

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ABSTRACT

Boyd, L., Grant, P., Lemieux, J. and Iacarella, J.C. 2022. Cumulative Effects of Threats on At-Risk Species Habitat in the Fraser Valley, British Columbia. Can. Manuscr. Rep. Fish. Aquat. Sci. 3243: viii + 65 p.

Freshwater species are experiencing the cumulative effect of numerous habitat threats from anthropogenic and natural disturbances on the landscape. In particular, a variety of threats have been attributed to declines in freshwater fish populations in the Fraser Valley, British Columbia, Canada with some declines severe enough to warrant designation as Species At Risk. However, our understanding of where these threats are most critical, and subsequently how and where to manage them, is limited for freshwater systems. We conducted a cumulative effect assessment to identify levels of landscape-based threats for habitat of at-risk fish species in relation to the extent of the Fraser Valley to begin developing priorities for management of threats and fish habitat. We performed this assessment for eight at-risk fish species with important habitat in the Fraser Valley (Salish Sucker, Nooksack Dace, Mountain Sucker, White and Green Sturgeon, Coastrange Sculpin, Sockeye, and Chinook Salmon) and seven key habitat threats (pollution, sedimentation, nutrients, riparian disturbance, aquatic habitat destruction, aquatic invasive species, and habitat fragmentation). We applied spatial data of landscape disturbances to estimate threat levels locally (e.g., barriers to passage) or based on upstream catchment area and flow accumulation (e.g., nutrients). We evaluated threats levels individually and as an additive cumulative effect score for each species' habitat to determine which threats may be the most problematic and which species and habitats are likely experiencing the greatest impacts. For instance, Nooksack Dace and Salish Sucker had the highest cumulative effect score in their habitat, with pollution as the most prominent contributing threat. This information can be used by managers to identify specific habitats and threats that may be of immediate concern in the protection and remediation of at-risk species habitat.

RÉSUMÉ

Boyd, L., Grant, P., Lemieux, J. and Iacarella, J. 2022. Cumulative Effects of Threats on at-risk Species Habitat in the Fraser Valley, British Columbia. Can. Manuscr. Rep. Fish. Aquat. Sci. 3243: viii + 65 p.

Les espèces d'eau douce subissent l'effet cumulatif de nombreuses menaces sur l'habitat découlant de perturbations anthropiques et naturelles dans le paysage. Plus particulièrement, on a attribué diverses menaces au déclin des populations de poissons d'eau douce dans la vallée du Fraser (Colombie-Britannique, Canada), certains déclins étant suffisamment graves pour justifier la désignation d'espèces en péril. Cependant, notre compréhension des endroits où ces menaces sont les plus critiques, et par conséquent comment et où les gérer, est limitée pour les systèmes d'eau douce. Nous avons effectué une évaluation des effets cumulatifs afin de déterminer les niveaux des menaces à l'échelle du paysage pour l'habitat des espèces de poissons en péril par rapport à l'étendue de la vallée du Fraser, et ce, dans le but de commencer à établir des priorités pour la gestion des menaces et de l'habitat des poissons. Nous avons réalisé cette évaluation pour huit espèces de poissons en péril dont l'habitat est important dans la vallée du Fraser (meunier de Salish, naseux de Nooksack, meunier des montagnes, esturgeon blanc et vert, chabot côtier, saumon rouge et saumon chinook) et sept menaces clés pour l'habitat (pollution, sédimentation, nutriments, perturbation des berges, destruction de l'habitat aquatique, espèces aquatiques envahissantes et fragmentation de l'habitat). Nous avons appliqué les données spatiales des perturbations du paysage pour estimer les niveaux de menace à l'échelle locale (p. ex. les obstacles au passage) ou en fonction du bassin versant en amont et de l'accumulation des débits (p. ex. les nutriments). Nous avons évalué les niveaux de menace individuellement et sous la forme d'un score d'effet cumulatif additif pour l'habitat de chaque espèce en vue de déterminer quelles menaces peuvent être les plus problématiques et quelles espèces et quels habitats sont les plus susceptibles de subir les effets les plus importants. Par exemple, le naseux de Nooksack et le meunier de Salish avaient le score d'effet cumulatif le plus élevé dans leur habitat, la pollution constituant la menace la plus importante. Les gestionnaires peuvent utiliser ces renseignements pour déterminer les habitats et les menaces spécifiques qui peuvent constituer une préoccupation immédiate dans la protection et la restauration de l'habitat des espèces en péril.

INTRODUCTION

The Fraser Valley region of southwestern British Columbia (BC) is characterized by large floodplains between surrounding mountain ranges. The Fraser River mainstem is the major freshwater feature, extending along the valley floor and emptying into the Pacific Ocean at the Strait of Georgia. Many hydrologically connected lakes and streams are also present throughout the valley. Significant changes in land cover have occurred since European settlement in the region in 1827, including the increase in urban and agricultural land, and reduction of wetland and forested area (Boyle et al., 1997). Amid continued intensifying urbanization and agricultural practices, land, forest, and water resource use has increased and water quality in the Fraser Valley region has declined (Hall and Schreier, 1996; MacDonald 2005). Twenty-five years ago, it was already estimated that the great majority of pre-settlement streams in the Fraser Valley had been effectively lost through alteration and culverting, and the remaining streams were significantly altered through channelization, diversion, and riparian zone degradation (DFO, 1997). The Fraser Valley is among the fastest growing regions in BC (Statistics Canada, 2022), which places further strain on ecosystems in the region.

The Fraser River Basin is considered a ‘Priority Area’ by Fisheries and Oceans Canada for aquatic species at risk. The health of freshwater ecosystems within the Fraser Valley is important as it supports 31 freshwater fish species with a broad range of habitat needs to sustain viable populations. Of these fish species, ten are considered at-risk populations as of February 2022 by either the federal *Species At Risk Act* (SARA), and/or the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), which conducts assessments on all relevant species. Additionally, many at-risk salmonid populations rely on the region as spawning adults, and as rearing and out-migrating juveniles. Many of these at-risk species, particularly White Sturgeon and Chinook and Sockeye Salmon, are economically, culturally, and recreationally significant (DFO, 2020a).

Geospatial cumulative effect assessments are becoming an important tool for estimating the threat levels or impacts of simultaneous pressures on species and their habitats. The basis of these assessments is the mapping and quantification of human activities or threats that are known to impact a focal ecological component (Murray et al. 2020). Such cumulative effect assessments use spatial layers of human activities and landscape disturbances (hereafter both are referred to collectively as landscape disturbances) as proxies of pressures as this information is most readily available (Halpern and Fujita, 2013; Seitz et al. 2011). Marine and terrestrial, and also often freshwater, cumulative effect assessments generally apply direct overlays of landscape disturbances to an ecological component such as species’ habitat. However, accurately estimating threats from landscape disturbance in freshwater systems requires consideration of accumulation downstream of disturbances (Beechie 2021; Linke et al. 2019). Once mapped, threats can be standardized as a risk score or binned into risk levels based on known thresholds or statistical data distributions and, in some cases, assigned vulnerability weightings based on expert opinion. The final cumulative effect score is typically a summation of the (weighted or unweighted) risk scores (Halpern and Fujita, 2013) or a further combination of the risk scores into binned cumulative effect levels (e.g., ‘green’, ‘amber’, ‘red’ levels; Conners et al., 2018;

Davidson et al., 2018). The final product of a geospatial cumulative effect assessment provides relative scores across a study area that enables identification of priority areas for management actions (Halpern and Fujita, 2013; Murray et al., 2020).

Freshwater cumulative effect assessments that have spatially encompassed, or been adjacent to the Fraser Valley region to-date include the Pacific Salmon Explorer from the Pacific Salmon Foundation (www.salmonexplorer.ca; Connors et al., 2018) and provincial assessments for the Elk Valley region in the Columbia River watershed (Davidson et al., 2018). These assessments identify and map landscape disturbances at the watershed level using direct overlays, either as proxies for rolled up impact categories (e.g., water quality) or as indicators that are then qualitatively related to potential threats, respectively. Estimating individual threats, such as sedimentation levels, for freshwater across a landscape ideally involves statistical or process-based spatial models and extensive *in situ* data for model parameterization and validation (Beechie, 2021). However, *in situ* data is greatly limiting for large spatial extents. Here, we advance current cumulative effect assessments for the region by (1) estimating threat levels based on downstream effects of landscape disturbances in relation to stream network flow direction and catchment size, (2) conducting the assessment at a stream reach resolution, and (3) evaluating a comprehensive list of threats identified as critical for at-risk fish in the region. Our assessment of freshwater habitat threats from landscape disturbances is a first step towards modeling threat levels and obtaining a more accurate picture of cumulative effects on fish habitat.

We evaluated threat levels from landscape disturbances (e.g., agriculture, forest fires) on important freshwater habitat for eight at-risk fish species in the Fraser Valley, BC to help guide prioritization of threat mitigation and habitat restoration. The species included Salish Sucker (*Catostomus* sp. cf. *catostomus)*, Nooksack Dace (*Rinichthys cataractae* ssp.), Mountain Sucker (*Catostomus platyrhynchus*), White Sturgeon (*Acipenser transmontanus*), Green Sturgeon (*Acipenser medirostris*), Coastrange (Pygmy) Sculpin (*Cottus aleuticus*), Sockeye Salmon (*Oncorhynchus nerka*), and Chinook Salmon (*Oncorhynchus tshawytscha*). We focused on the seven key threats that impact the habitat of these species as reported by COSEWIC through expert review: pollution, sedimentation, nutrients, riparian disturbance, aquatic habitat destruction, Aquatic Invasive Species (AIS), and habitat fragmentation. We identify which threats contribute most to cumulative effect scores for each species' habitat and across species' habitats relative to the extent of the Fraser Valley, and provide maps of cumulative effect scores across habitats. We also highlight research gaps and next steps for cumulative effect analyses. In particular, merits and details of the spatial analysis methods used for estimating each threat are discussed in detail to contribute to development of future cumulative effect assessments.

METHODS

Study Area

We defined the Fraser Valley extent as the 200 m elevation contour from the estuary to Hope, BC. A hydrologically meaningful boundary was created by including all assessment watersheds delineated by the Freshwater Atlas (BC MOE, 2017) that intersected the elevation contour. The study area was then clipped to only include areas within the Fraser Basin up to the Canada/US border. An additional area was added in the southwestern portion of BC (part of the South Coast Rivers Watershed) to encompass Nooksack Dace habitat that would have been otherwise excluded (Figure 1). To account for the threats that are affected by upstream disturbances (sedimentation, nutrients, and pollution), a hydrological buffer of 1:20,000 assessment watersheds was added to the study area.

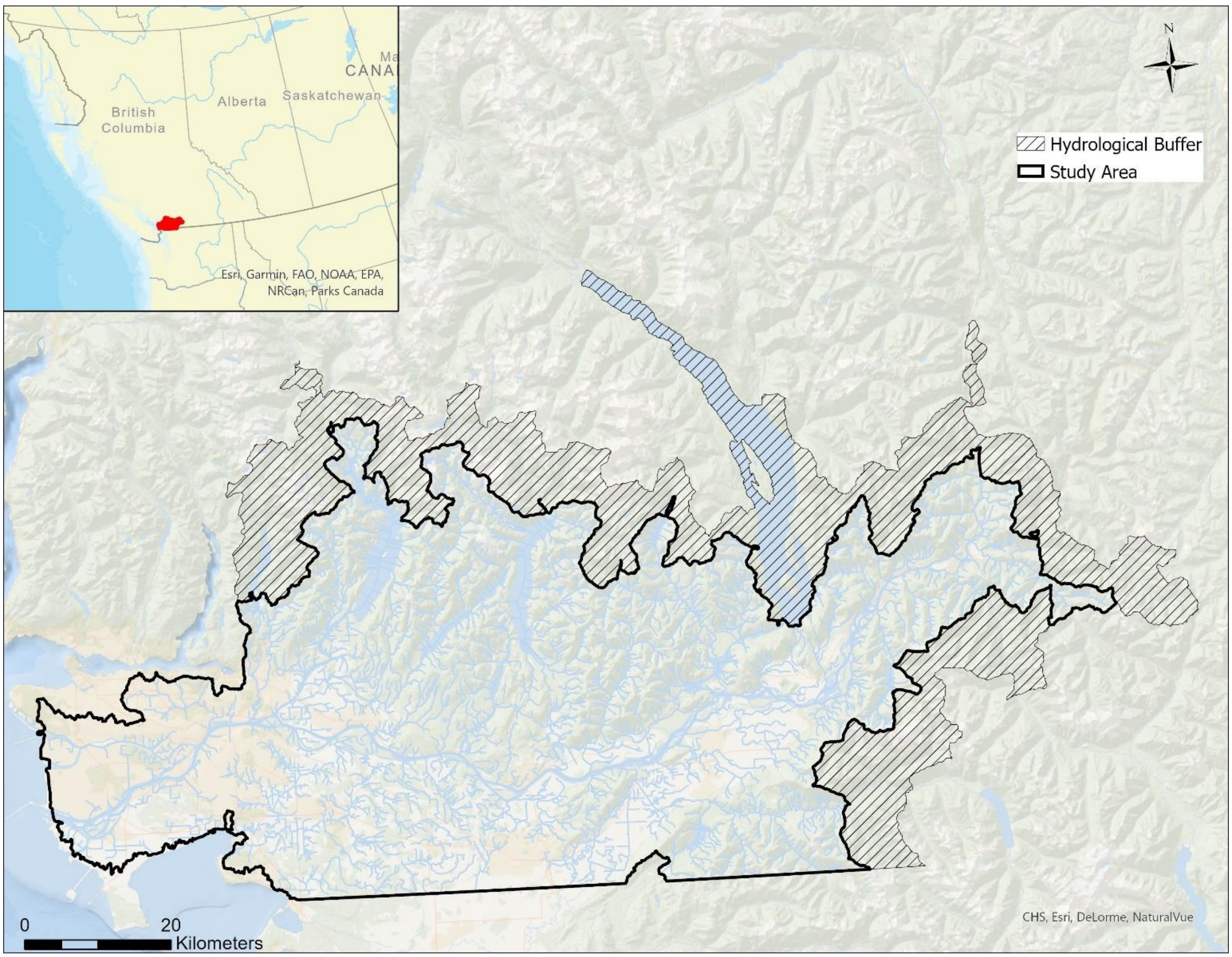


Figure 1. Study area extent in the Fraser Valley region with added buffer of 1:20,000 scale Freshwater Atlas Assessment watersheds to account for threats that have downstream effects.

Species and Habitat

We identified eight fish species that were listed under the *Species at Risk Act* (SARA) or assessed as threatened or endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), and were reliant on freshwater habitat in the Fraser Valley, as of November, 2021. Some species such as Eulachon were excluded from the study because the location and habitat use in their freshwater life stage is not well understood. Coho Salmon were also excluded as they pass through the study area, but do not have at-risk Designatable Units (DUs; defined by COSEWIC) within the study area.

We mapped important habitat along the stream network for each of the eight species using the best available data sources. Salish Sucker, Nooksack Dace, Mountain Sucker, Green Sturgeon, and Coastrange Sculpin habitats were mapped using DFO species distribution polygons for SARA-listed species. For White Sturgeon and salmon species, spawning locations were used to represent important habitat for adult spawners, egg incubation, and fry emergence. Provincial spawning location polygons were used to identify habitat patches for White Sturgeon. For the salmon species, only spawning habitat within threatened or endangered DUs were used. Spawning habitat for Chinook were developed from spawning lines originating from DFO and other sources, and provided online by the Pacific Salmon Explorer (www.salmonexplorer.ca; Connors et al., 2018). Spawning habitat for Sockeye were delineated from the Pacific Salmon Explorer spawning lines and DFO Stock Assessment spawning polygons. For all species, stream network lines that were encompassed or directly linked to polygons or lines were identified as species habitat. For habitat that was discontinuous along the stream network, connected stream reaches were grouped and numbered as distinct habitat patches.

Threat Identification

In order to identify the key threats impacting these species, we reviewed the most recent COSEWIC assessment and status reports for each species (COSEWIC, 2010, 2012, 2013, 2017, 2018, 2019). For Nooksack Dace and Salish Sucker, the most recent DFO recovery strategy reports were used to identify threats (DFO 2020b, 2020c) (Table 1). The overall importance of these threats was based on expert opinion and represents the current state of knowledge. Their relative importance for each species (i.e., the vulnerability of the species to a threat) has not yet been assessed.

Table 1. At-risk species included in the study and key threats (i.e., threats) identified by COSEWIC. Species with an asterisk (*) are listed under the *Species at Risk Act*.

Species	**COSEWIC Status**	**Impacted Life Stage**	**Listed Freshwater Environment Threats**
Salish Sucker*	Threatened	All	-Hypoxia -Seasonal lack of water -Harmful substances -Sediment deposition -Habitat fragmentation -Physical destruction of habitat -Increased predation from aquatic invasive species
Nooksack Dace*	Endangered	All	-Sediment deposition -Seasonal lack of water -Harmful substances -Physical destruction of habitat -Hypoxia -Riffle loss to impoundment -Habitat fragmentation
Mountain Sucker*	Pacific Populations: Special Concern	All	-Habitat loss and degradation associated with the expansion of agricultural, commercial and industrial land use -Introduction of aquatic invasive species -Low flows and high temperatures from climate induced drought and surface water extractions -Gravel extraction -Dam and reservoir construction
White Sturgeon	Lower Fraser River Population: Threatened	All	-Habitat degradation and fragmentation from dam construction and changes to flow regime -Dikes, dredging, gravel mining, commercial fisheries by-catch, incidental mortality from catch-and-release recreational fisheries, declines in important forage fishes, and introduced species
Green Sturgeon*	Special Concern	Feeding and migration refugia	-Water use (extraction, dams, diversions, flow regulation) -Land use (sediment) -Pollution (effluent discharges)
Coastrange Sculpin* (Pygmy Sculpin)	Cultus Lake Population: Endangered	All	-Predation from Smallmouth Bass and other invasive species -Reduced hypolimnetic oxygen caused by human development and eutrophication -Increased epilimnetic temperatures

Sockeye Salmon	River Type: -DU24 Widgeon: Threatened Lake Type: -DU10 Harrison Upstream: Endangered -DU6 Cultus Lake: Endangered	River Type DU 24: Spawn in river, fry head to estuary shortly after hatch Lake Type DU 10: Spawn in river, juveniles spend 1 year in Harrison Lake DU6: Adults enter the lake and remain for ~4 months before spawning. Juveniles spend 1 year in Cultus Lake	-Overfishing -Industrial effluents, landslides -Freshwater temperature extremes
Chinook Salmon	-DU2 LFR-Harrison: Threatened -DU4 LFR-Upper Pitt: Endangered -DU5 LFR-Summer: Threatened	DU2: Ocean-type; Spawn in river, head to estuary shortly after hatch DU4: Stream-type; Spawn and spend 1+ year in freshwater DU5: Stream-type; Spawn and spend 1+ year in freshwater	-Overharvest -Increased temperatures -Climate changes to flow regimes through reduced glacier size and altered precipitation and snowpack patterns -Pollutants from industrial discharge, storm water runoff, and sewage and agricultural runoff

COSEWIC-reported threats were linked to the contributing landscape disturbances in an area-based Pathway of Effects framework for the Fraser Valley (Murray et al., 2020). COSEWIC reports identified threats in the context of landscape disturbances, but did not always associate disturbances with specific threats. We applied linkages based on known disturbance-threat-ecological pathways from the primary literature (detailed below), where landscape disturbances can contribute to one or multiple threats. We focused this initial cumulative effect assessment on the landscape-driven threats, including aquatic invasive species, habitat fragmentation, physical destruction of aquatic habitat, riparian zone disturbance, pollution, sedimentation, and nutrients (Figure 2). Statistical models are in development for addressing water state threats including low water flow, high water temperature, hypoxia, and climate change (e.g., projected changes in water temperature and flow) for this region and will be applied to future cumulative effect assessments (D. Weller, J.C. Iacarella, unpublished data). Overharvest was not included within the scope of the assessment as this is not a habitat-specific threat. In order to fully investigate potential threats to the at-risk species within the region, all identified threats were applied across species whether or not they were specified for a particular species.

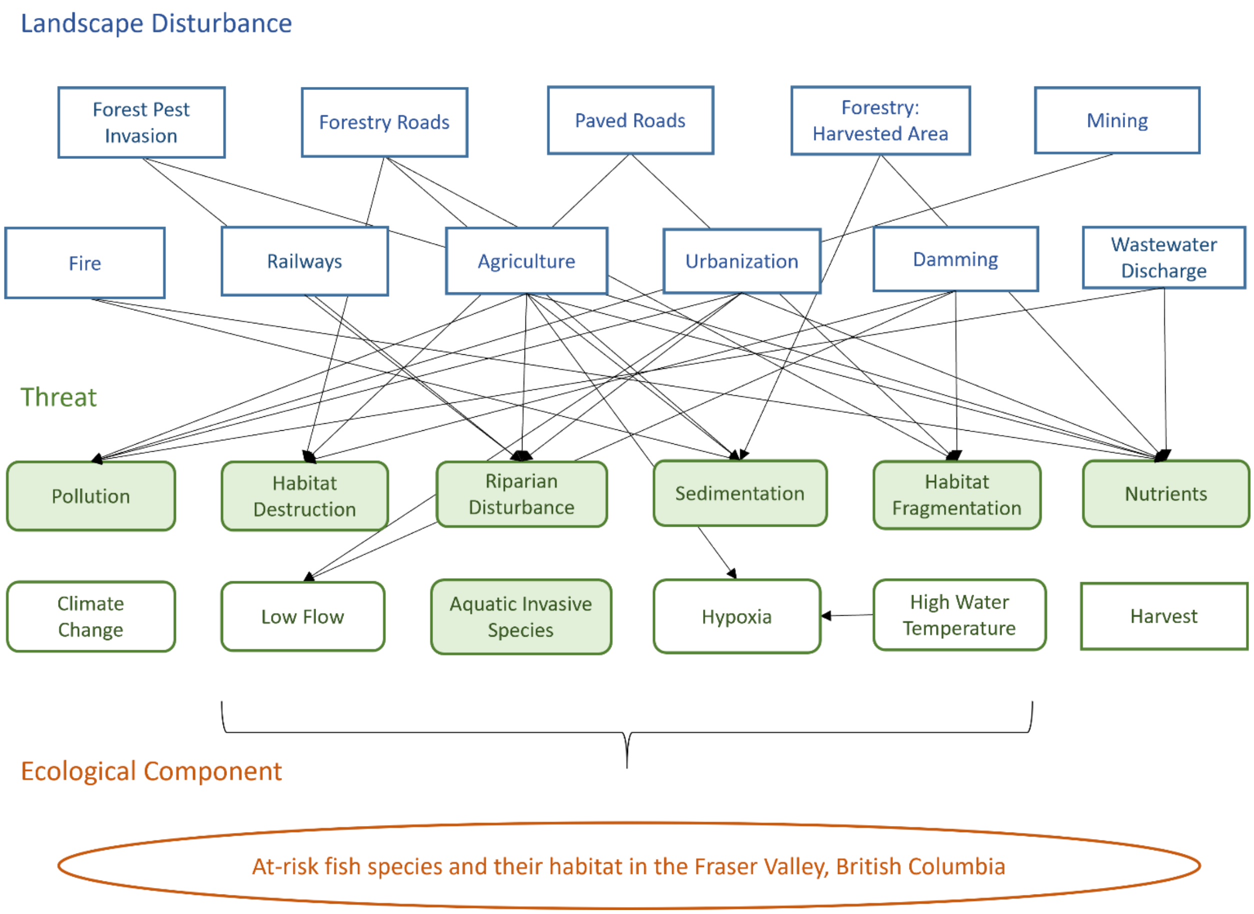


Figure 2. Pathway of Effects framework showing the connections of landscape disturbances, threats, and ecological components in the Fraser Valley, BC. The cumulative effect assessment presented here was conducted for the landscape-driven threats (light green boxes), and environmental and harvest threats (white boxes) are in development for future assessments.

Threat Analysis and Mapping

The analysis and mapping of threats was based on identifying landscape disturbances and development on the landscape (e.g., agriculture, paved roads) that are known to contribute to the threat in the freshwater environment, and calculating downstream effects when relevant. Spatial landscape disturbance data layers that were applied to each threat is detailed in Appendix A1.

The linear hydrologic network used for mapping and analyses was a union of rasterized BC Provincial Freshwater Atlas 1:20,000 stream network and a hydro-modelled stream network (D. Weller, unpublished data) with minimum catchment size of 0.25 km^2 and gridded at a 25 m resolution. This linear hydrologic network runs through connected lakes and large rivers (e.g., the Fraser River Mainstem) on the landscape. Specific hydrologic impacts from lakes and rivers are complex and were not included in these analyses. Instead, we treated large rivers and lakes the same as streams so that we could assess important habitat in these systems (hereafter referred to as ‘the stream network’); future models can be improved by addressing differences in threat accumulation between lakes, rivers, and streams. All mapped landscape disturbance data layers were subsequently rasterized and rescaled to a 25 m resolution as appropriate, and all threat outputs and cumulative effect scores were developed for the same 25 m grid. In order to make the data comparable to the other threats when added into the final cumulative effects scoring, the AIS and fragmentation scores were scaled between 1 and 0, where the highest value became 1 and lowest remained at 0. This was completed using the formula $z_i = (x_i - \min(x))/ \max(x) - \min(x)$, where z_i is the normalized value, x_i is the i^{th} value in the dataset, min(x) is the minimum value in the dataset, and max(x) is the maximum value in the dataset. At-risk species habitat patch data was subsequently overlaid to determine scoring for specific habitat areas, however calculations have been completed for all stream reaches within the Fraser Valley. All spatial analyses were completed using ArcGIS Pro version 2.8 (ESRI Redlands, CA).

Flow Accumulated Threats

Downstream effects of landscape disturbance were calculated for sedimentation, nutrient, and pollution threats. Threat values were calculated as a fraction of the upstream catchment area occupied by landscape disturbances that contributed to the focal threat in the downstream grid cell (Figure 3). For instance, a grid cell along a stream with a large upstream catchment area and few landscape disturbances would have a low threat value because those disturbances would become diluted. Conversely, streams with little upstream catchment area would be more heavily influenced by landscape disturbance. The Flow Accumulation tool in ArcGIS Pro was used to calculate the catchment size at each grid cell along the stream network (i.e., total area of land that drains into that cell) and the total number of cells with ‘present’ contributing landscape disturbances. Multiple contributing disturbances in a grid cell were treated as one ‘presence’ so as to not over-account for highly dense but localized disturbances in a catchment. The proportion of catchment area covered by a landscape disturbance that contributed to the threat at each stream network grid cell was then calculated. For example, if a grid cell along the stream network had an upstream catchment size of 10 km^2 and 1 km^2 of that catchment was classified with disturbances contributing to the threat, then the flow accumulated threat value would equal 0.1.

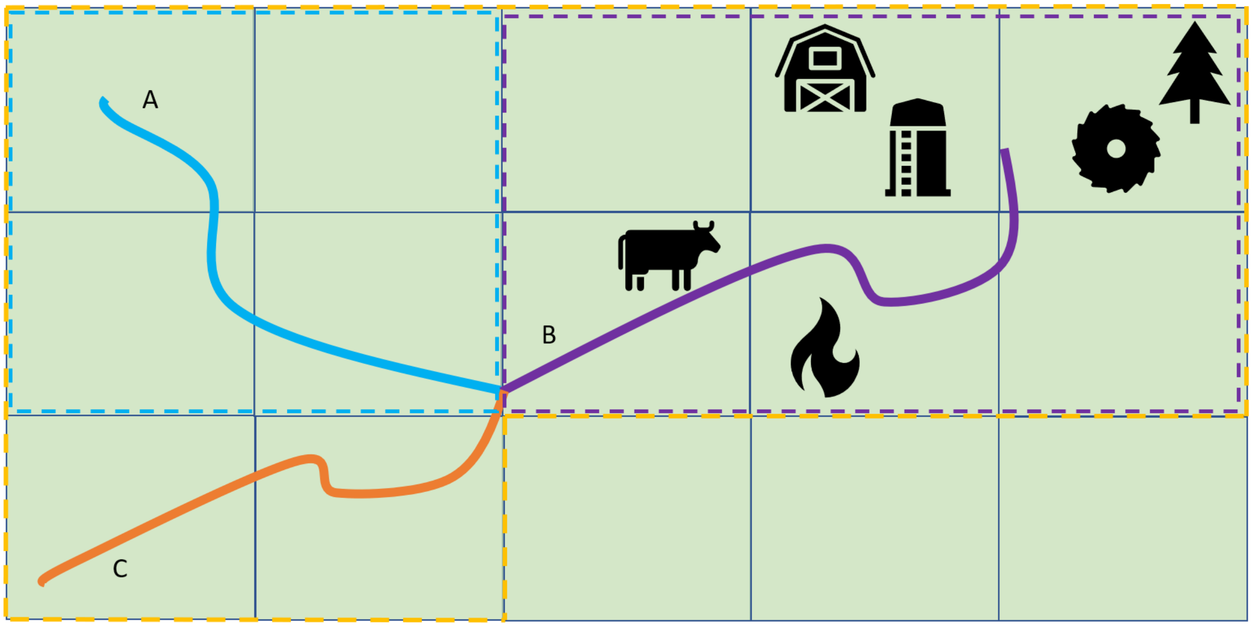


Figure 3. Stream reaches with associated catchment areas (dashed lines). Stream reach A would have a sedimentation threat score of 0, reach B would score 0.67, and reach C would score 0.33 (proportion of impacted cells per catchment area). The larger catchment area of reach C dilutes the landscape disturbance inputs from upstream.

Sedimentation

Sedimentation is a natural and necessary part of a healthy freshwater ecosystem, but altered landscapes create events and conditions for more frequent pulses and greater volumes of sediment to wash into water courses that can be deleterious to fish habitat. High levels of sediment can cause a variety of lethal and sublethal impacts for freshwater species including smothering incubating eggs (Scrivener and Brownlee, 1989) and altering foraging arenas and benthic vertebrate prey community composition (Champion et al., 2018; Shaw and Richardson, 2001). To determine areas on the landscape that contain disturbances that contribute to sedimentation, a land cover mosaic was created using (1) agricultural land cover, (2) mines, (3) maintained and unmaintained gravel roads, including forestry roads, (4) forested areas that were burned within the last ten years, and (5) forested areas that were harvested within the last ten years. This land cover mosaic was used in the flow accumulation methods described above.

Agricultural areas and range lands contribute to sedimentation through fine-grained, exposed top layers of soil washing into nearby water courses (Owens et al., 2005). Mines, particularly aggregate and gravel mines, disturb the topmost layers of soil allowing for large sediment pulses during mining activities and runoff events (BC MOE, 2015).

Gravel roads and forestry roads are well known contributors to sedimentation during the construction phase (Lachance et al., 2008; Orndorff, 2017). Unpaved roads also act as a sediment source during resurfacing, traffic use, and runoff events (Demir et al., 2012). Sediment inputs decrease as roads age, but increase again when roads are resurfaced (Luce and Black, 2001). Thus, all ages of gravel and forestry roads were used in this analyses.

Forested areas that have been burned by wildfire contribute large quantities of sediment and ash to stream networks as vegetation is removed and the top-most layers of soil become dry and exposed (Ryan et al., 2011). The effects of initial loading decrease after approximately three years, and have been found to return to pre-burn levels after approximately eight years when sufficient regrowth has occurred (USDA, 2014). For this study, we have used a conservative ten-year temporal cut off for areas that have been burned.

Similar to burned areas, areas harvested for forestry have also been found to contribute significant quantities of sediment as vegetation is removed. These effects also decrease after approximately six years (Gomi et al., 2005). For our analyses, we used a ten year temporal cut-off as a slight over estimate in order to ensure sediment sources were fully captured.

Nutrients

Increased nutrient levels (particularly nitrogen and phosphorus) typically create issues in freshwater systems by supporting high levels of vegetation and algal growth (Schindler 1974). High levels of algae and vegetation can create hypoxic conditions through decomposition of dead algae and diurnal extremes in macrophyte photosynthesis and respiration (Harper, 1992). Hypoxic conditions are known to cause sublethal and lethal effects on fish, and is a major concern in the streams within the Fraser Valley (Rosenfeld et al., 2021). To determine areas on the landscape that contain disturbances that have high nutrient input, a land cover mosaic was created using (1) agricultural land cover, (2) areas burned within the last ten years, (3) areas that have been harvested within the last ten years, (4) waste water discharge areas, and (5) areas that have been defoliated by pests. This land cover mosaic was used in the flow accumulation model as described above.

Agricultural areas contribute high levels of nutrients to nearby freshwater surface and groundwater sources have high nutrient input through multiple pathways including runoff and erosion of overfertilized soils and (Carpenter, 2005; Schröder et al., 2004). Rangelands supporting livestock and poultry also contribute nutrients to freshwater systems through improper manure management (Sutherland, 2006).

Burned areas contribute nutrients to stream networks through the removal of vegetation, soil disturbance, and surface hardening. Without sufficient vegetated cover to uptake nutrients and less pervious surface soils, they are easily flushed through the ground and into the stream network. High levels of bioavailable nutrients have been found in riverine systems up to seven years after burns have occurred (Emelko et al., 2016; Silins et al., 2014). In order to fully capture areas affected by burns, a conservative ten-year cut off for burned areas was used.

Similar to burned areas, areas harvested for forestry have also been found to contribute significant quantities of nutrients as vegetation is removed and nutrients are easily flushed into freshwater systems (Pike et al., 2010). Significant increases of nutrients in adjacent water bodies have been seen 6-12 years post-harvest (Jewett et al., 1995; Palviainen et al., 2015). Though the type of harvest impacts the amount of nutrient input (Mupepele and Dormann, 2017), in lieu of this data, we included all harvest areas with a ten-year cutoff within the study area.

Municipal waste water discharge areas are well known contributors to nutrients causing eutrophication and associated hypoxia in freshwater systems (Chambers et al., 1997). Impacts are greatest at the discharge source, but influence downstream environments as well (Tetreault et al., 2012). For our analyses, only point source spatial information was available, so waste water discharge areas were represented on the landscape as a single 25 m grid cell. This potentially underestimates the impacts of waste water discharge areas on freshwater habitat.

Forested areas that have been defoliated by pests can cause increased localized nutrient input if the vegetation is damaged beyond its capacity to function normally and uptake nutrients (Connors et al., 2018). Only areas that have been defoliated within the last ten years and had 'severe' and 'very severe' levels of pest infestation were incorporated as these were most likely to have larger impacts on the freshwater environment given how nutrients are flushed into the system from harvested or burned areas.

Pollution

Pollution is a broad term, generally used to characterize any substance (including sediment and nutrients) that flows into a water system that can cause damage to fish and fish habitat at high quantities. In this case, we used the term pollution to encompass inputs other than sedimentation and nutrients such as hormones and heavy metals. To determine areas on the landscape that contain disturbances that are pollution sources, a land cover mosaic was created using (1) agricultural land cover, (2) urban land cover, (3) paved roads, (4) mines, and (5) waste water discharge areas. This land cover mosaic was then used in the flow accumulation model described above.

Agricultural areas and areas supporting livestock contribute a variety of pollutants such as herbicides, pesticides, fungicides, and veterinary pharmaceuticals that are flushed into adjacent water courses. These inputs have been shown to cause direct impacts such as fish toxicity, anoxic conditions, and endocrine disruption, as well as indirect impacts through food web disruption and habitat degradation (Berka et al., 2001, Evans et al., 2012). Estrogen mimicking agro-chemicals and pesticides have been shown to cause endocrine disruptions, resulting in reproduction and population challenged for fish (Okoumassoun et al., 2002; Evans et al., 2012).

Urban areas and roads are major sources of pollution, primarily through stormwater runoff over impervious surfaces that flush heavy metals and other contaminants into freshwater systems. Following storm events, trace metals are frequently found in streams at levels exceeding water quality criteria for the protection of aquatic life (Hall et al., 1998; Sekela et al., 1998). These pollutants get flushed through the freshwater environment, but many settle in sediment and remain bioavailable to aquatic life (Li et al., 2009).

Mines have the potential to pollute adjacent freshwater environments in a variety of ways including surface runoff from exposed mine sites, leachate from abandoned mines, and tailing spills (Azcue et al., 1995; Byrne et al., 2018). The most common form of pollution from mines is heavy metals (e.g., arsenic) that have been shown to impact freshwater species (Grout and Levings, 2001).

Municipal waste water discharge areas pollute the environment with pharmaceutical compounds (e.g., excess estrogen) that have been shown to cause endocrine disruption and feminization of some fish species (Jeffries et al., 2010; McMaster, 2005). These impacts can cause population dynamic and reproductive challenges for affected fish (Evans et al., 2012).

Aquatic Invasive Species

Aquatic invasive species pose a threat to fish and fish habitat by overgrowing or altering habitat, competing for food or habitat resources, or preying on native species. Not all non-native, introduced species are invasive (i.e., spread and have a deleterious impact), though greater numbers of non-native species can shift food webs and ecosystem dynamics (Simberloff and Von Holle, 1999). Native species richness, particularly at-risk species, has been found to decline with greater non-native species richness in freshwater habitats (Dextrase and Mandrak, 2006; Nowosad and Taylor, 2013). We assessed the aquatic invasive species threat, using non-native species richness since individual impacts of these species on the at-risk native species is not currently well known. This threat is calculated more directly, using species data as opposed to disturbances that influence the spread and introduction of non-native species because species data were available in this case.

Publicly available data sources (detailed in Appendix A1) were filtered for aquatic non-native species and included 102 species of plants, fish, amphibians, reptiles, and aquatic birds. The mean non-native species richness was calculated for each stream reach within the Fraser Valley. These values were rescaled as described above to provide an aquatic invasive species score comparable to the other threats for the final cumulative effect summation.

Habitat Fragmentation

Habitat fragmentation is a major concern for both migratory species and resident species with limited habitat range (Finn et al., 2021; DFO, 2020c). Barriers that fragment habitat can cause issues with population dynamics and resilience, and genetic variation (Schlosser and Kallemeyn, 2000). Ecological barriers such as beaver damming and water velocity barriers are not temporally consistent and may not be a barrier for all freshwater species. We only considered artificial dams as absolute barriers causing fragmentation on the landscape, and to focus the analysis on anthropogenic-induced fragmentation. Similar to the aquatic invasive species threat, fragmentation was calculated in a more direct manner since data were readily available.

Presence of dams within the stream network was used to calculate potential for habitat fragmentation as the mean number of dams per stream reach. These values were rescaled as described above to provide a habitat fragmentation score comparable to the other threats.

Riparian Zone Disturbance

The riparian zone is commonly defined as the area 30 m from the water's edge (DFO, 2020d; *Riparian Areas Protection Regulation, 2019*, (BC Reg 178/2019) s. 8). The riparian zone is crucial to freshwater habitat health by providing key ecosystem services such as runoff filtration, shading that decreases stream temperatures, and bank stabilization (DFO, 2020d; Pusey and

Arthington, 2003). Disturbance to the vegetation in the riparian zone will negatively impact its ability to provide these critical ecosystem services to the freshwater environment.

To calculate the level of disturbance in the riparian zone, a 30 m buffer was created around streams, large rivers, and lakes within the Fraser Valley. The binary disturbance layer was developed using a mosaic of relevant disturbance raster layers including (1) urban area, (2) agricultural land, (3) mines, (4) all roads, (5) areas defoliated by pests, (6) burned areas from the last ten years, (7) forest areas harvested in the last ten years, and (8) rail lines. The same ten-year temporal limits used in the nutrient, pollution, and sedimentation threats were placed on the defoliated areas, burned areas, and harvested areas, as these types of landscape disturbances regrow over time. Any grid cells within the riparian zone containing these disturbances were considered to be disturbed. Riparian zone disturbance was reported as a proportion of the riparian zone area per stream reach, where a value of 1 would represent a riparian zone that is completely disturbed. The stream network used in this analysis runs down the center of the Fraser River mainstem and lakes. In these instances, the riparian zone data from the lakes and mainstem were linked to the nearest reach in the linear stream network.

Physical Destruction of Aquatic Habitat

Any anthropogenic activity that may have physically altered the aquatic landscape and habitat features within a water course was considered to create physical destruction of aquatic habitat. Though some natural events may cause habitat destruction, we focused on human activities for the cumulative effect assessment. Physical destruction of freshwater habitat is of concern because it can significantly alter fish and prey communities (Rempel and Church 2009). To calculate areas where physical destruction of aquatic habitat has taken place, a binary activity layer was developed using a mosaic of raster layers including (1) mines within 30 m of a water body, (2) dams, and (3) stream crossings.

Mines within 30 m of water courses can impact the stream by having infrastructure within the water body or by harvesting aggregate and gravel from the river itself. Significant sediment and gravel mining is known to take place in the Fraser Valley (McLean et al., 2006). Spatial data available did not have mine type information, so all mine footprints were used in this analysis. Areas where roads intersected water courses were also considered to have some form of associated aquatic habitat destruction. Road crossings were represented as a single grid cell on the landscape where the roads crossed the streams. Further refinement of spatial data on culverts and stream crossings would be beneficial for future calculations of this threat. Dams were also included, as detailed for the habitat fragmentation threat.

The final activity mosaic was overlaid with a rasterized freshwater network within the study area that included streams, lakes, and large river areas to assess the area of aquatic habitat that is impacted. Physical destruction of aquatic habitat was reported as a proportion of freshwater habitat area that was disturbed. These values were linked to corresponding stream reaches within the stream network. A value of 1 would represent a stream reach where 100% of the freshwater area is disturbed.

Threat and Cumulative Effect Scoring

Cumulative effect scores were calculated as the sum of all threats (individually scaled between 0 and 1) per stream reach (including segments running through the Fraser River mainstem and lakes). Threat and cumulative effect scores were summarized in the following ways: (1) mean individual threat score per stream reach (2) mean cumulative effect scores (summed threat scores) per stream reach (3) mean individual threat scores averaged across stream reaches identified as species habitat for each of the eight species (4) mean cumulative effect scores averaged across stream reaches identified as species habitat for each of the eight species (5) mean individual threat scores averaged across stream reaches identified as distinct habitat patches for relevant species, and (6) mean cumulative effect scores averaged across stream reaches identified as distinct habitat patches for relevant species. Threat and cumulative effect scores were also compared to the mean value for the Fraser Valley to provide an estimation of how impacted habitats are relative to the rest of the region. Maps were made representing cumulative effect scores by stream reach across the Fraser Valley and for each species' habitat extent to identify the areas that were estimated to be the most highly impacted.

All summary statics and graphing was conducted using R Statistical Software version 4.0 (R Core Team, Vienna, Austria).

RESULTS

Across the Fraser Valley, there is a general latitudinal trend with higher cumulative effect scores in the south and lower scores in the north (Figure 4). This trend corresponds with high levels of urban and agricultural land cover in the southern portions of the valley (Figure 5). Urban and agricultural land cover are incorporated into multiple threats including riparian disturbance, pollution and nutrients.

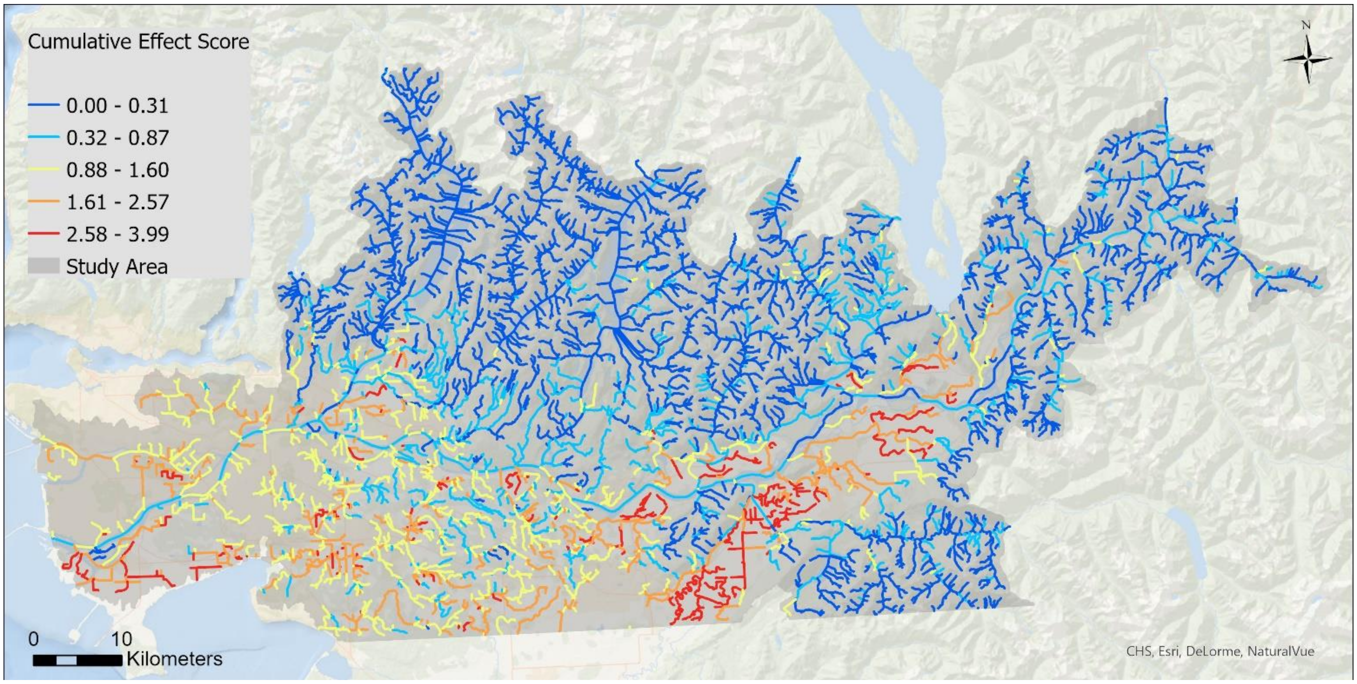


Figure 4. Cumulative effect scores for the Fraser Valley, BC stream network. Low cumulative effect stream reaches are in blue, and high cumulative effect stream reaches are in red.

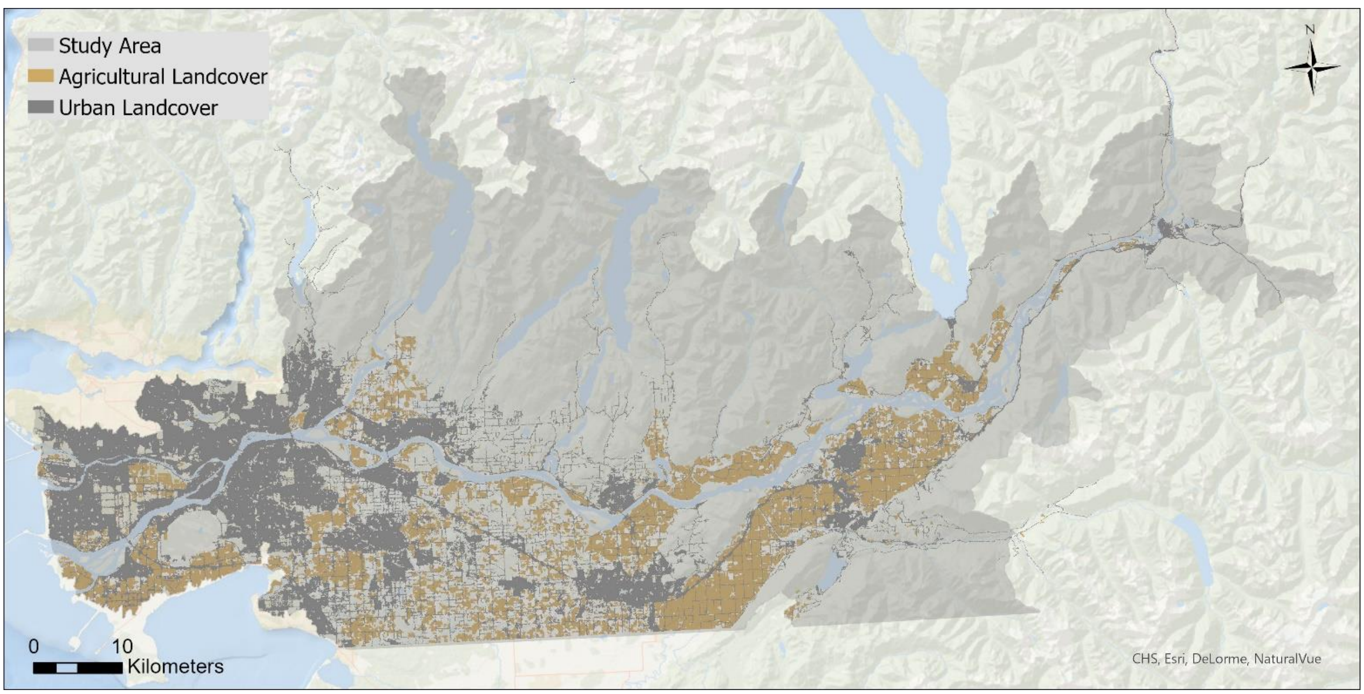


Figure 5. Agricultural (brown) and urban (dark grey) land cover within the Fraser Valley, BC.

The majority of threat scores for at-risk fish species habitat were much higher compared to threats averaged across the Fraser Valley stream network (Figure 6). Riparian zone disturbance and pollution were highest across the region and especially within at-risk species habitat compared to other threats, followed by sediment, nutrients, and non-native species richness. Riparian zone disturbance was highest within Salish Sucker habitat, and lowest within Sockeye Salmon habitat. Pollution was most prominent in Nooksack Dace habitat and lowest within Chinook Salmon habitat. Nooksack Dace and Salish Sucker habitat had the highest cumulative effect scores of all species, whereas Chinook Salmon and Sockeye Salmon had the lowest scores (Figure 7).

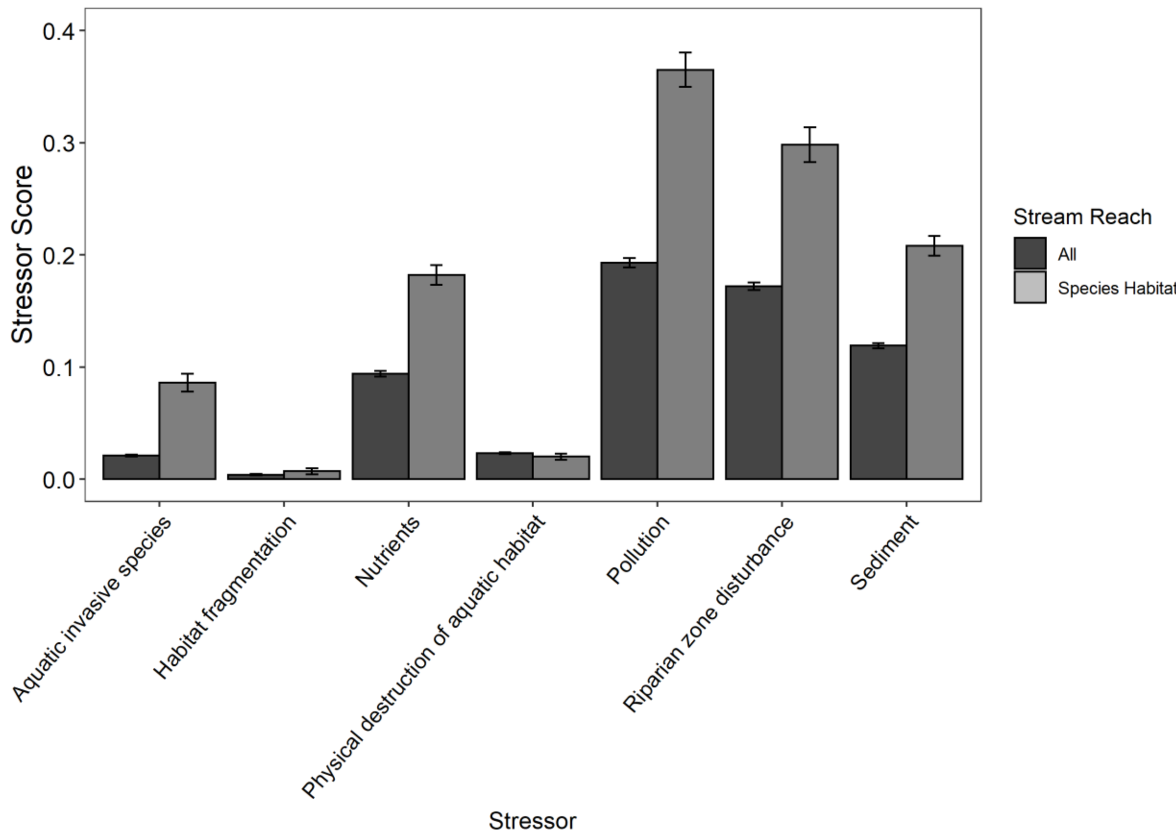


Figure 6. Scaled mean threat scores (0-1) for the stream network across the Fraser Valley (dark grey) and within important habitat of eight at-risk fish species (light grey). Bars are mean ± 1 SE.

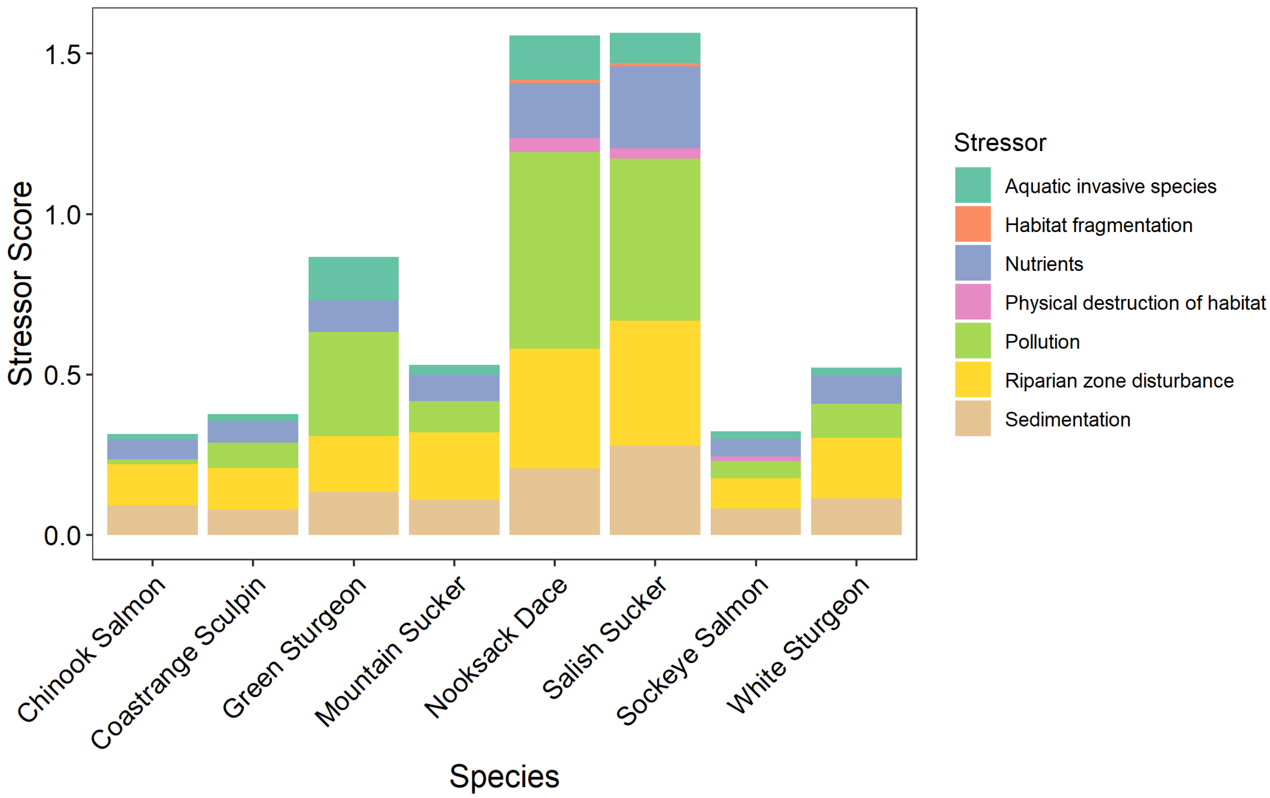


Figure 7. Stacked mean threat scores for at-risk species habitats. The top of the bar represents the mean cumulative effect score.

Chinook, Mountain Sucker, and Coastrange Sculpin had single habitat patches (Figures 8-10), whereas the other five species had discontinuous patches for which the importance of different threats varied (Figures 11-15). The major threat for species with discontinuous patches was generally consistent across patches, but contributions of relatively less significant threats were variable and resulted in different cumulative effect scores (Figures 11-15). For example, Nooksack Dace and Salish Sucker habitat patches were most affected by pollution (14 and 15), with habitat patches four and ten showing the highest cumulative effects, respectively. Threat and cumulative effect scores for all species and habitat patches are provided in Appendix Tables A2-A9.

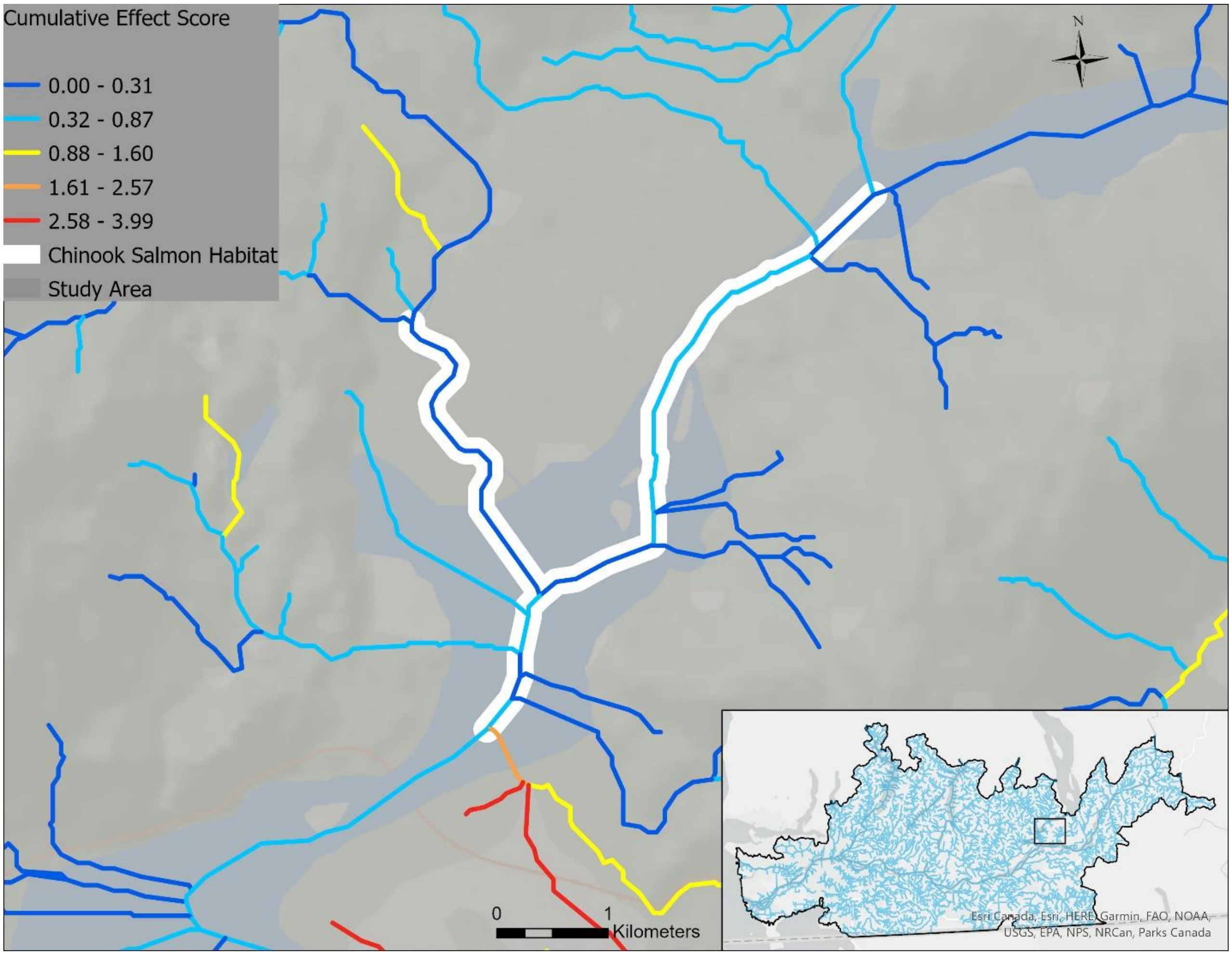


Figure 8. Chinook Salmon habitat (white outline) mean cumulative effect scores. The inset shows the location of the habitat patch within the Fraser Valley.

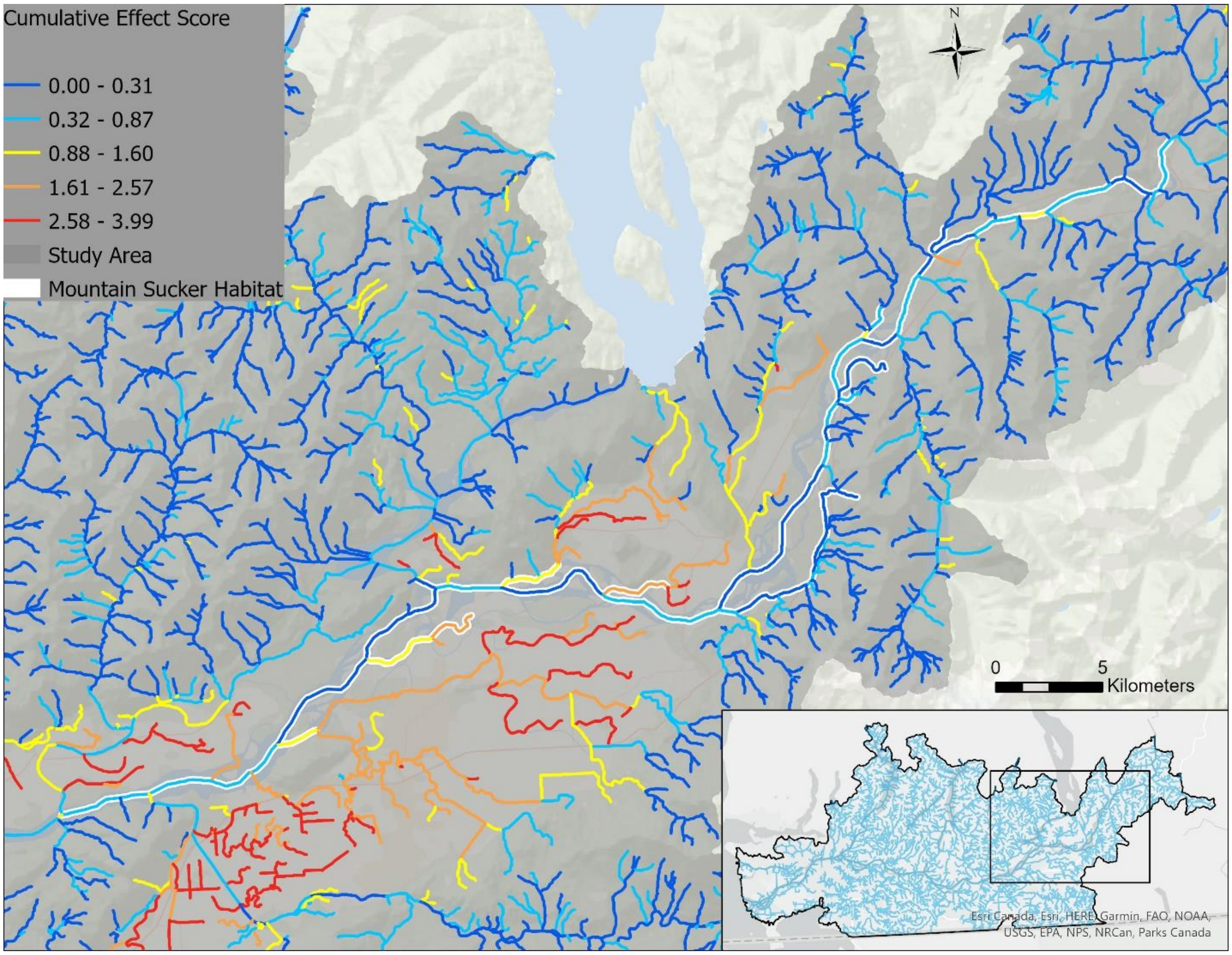


Figure 9. Mountain Sucker habitat (white outline) mean cumulative effect scores. The inset shows the location of the habitat patch within the Fraser Valley.

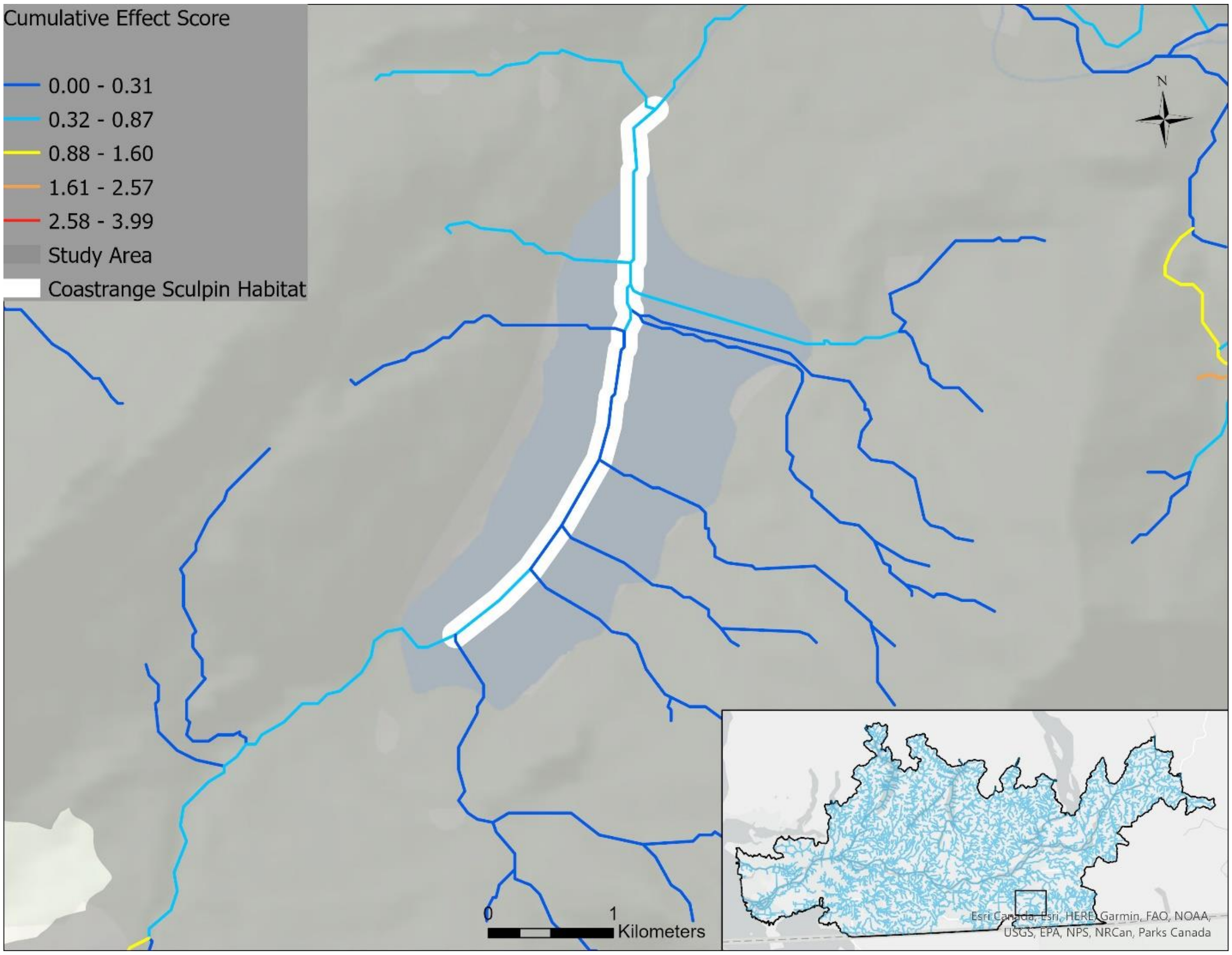
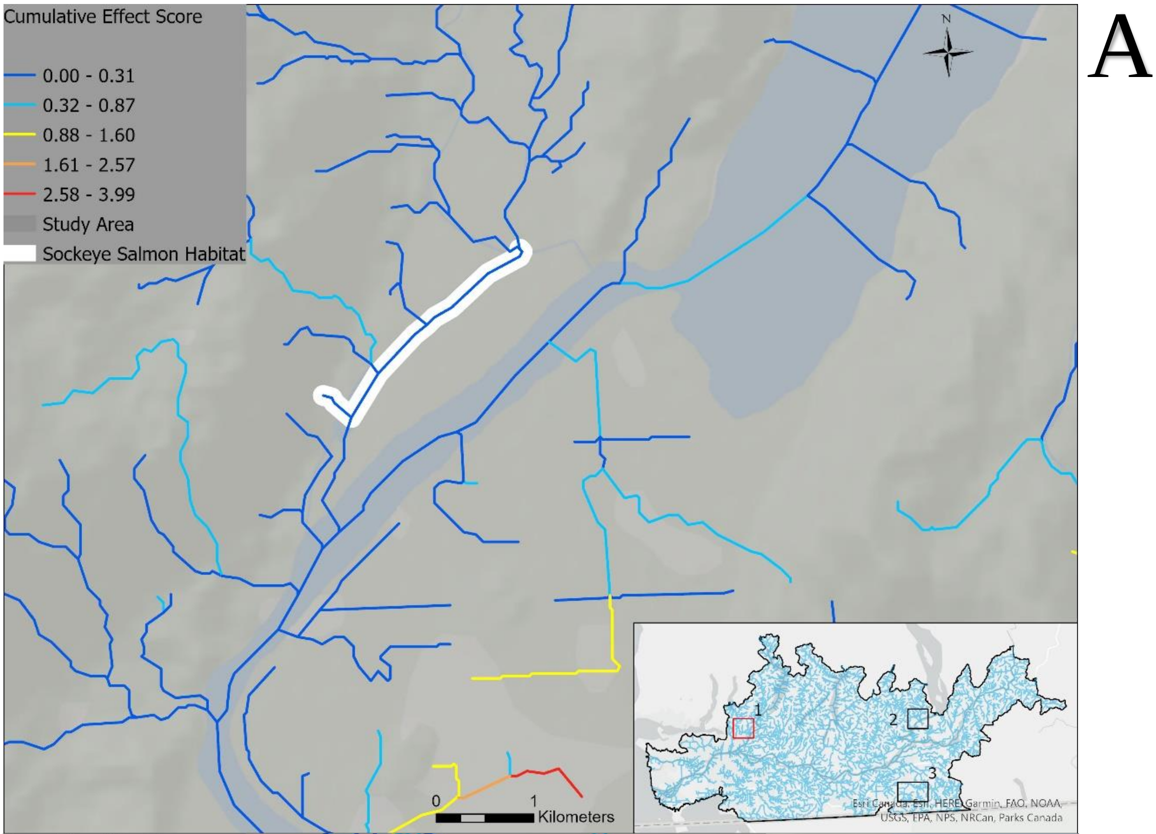
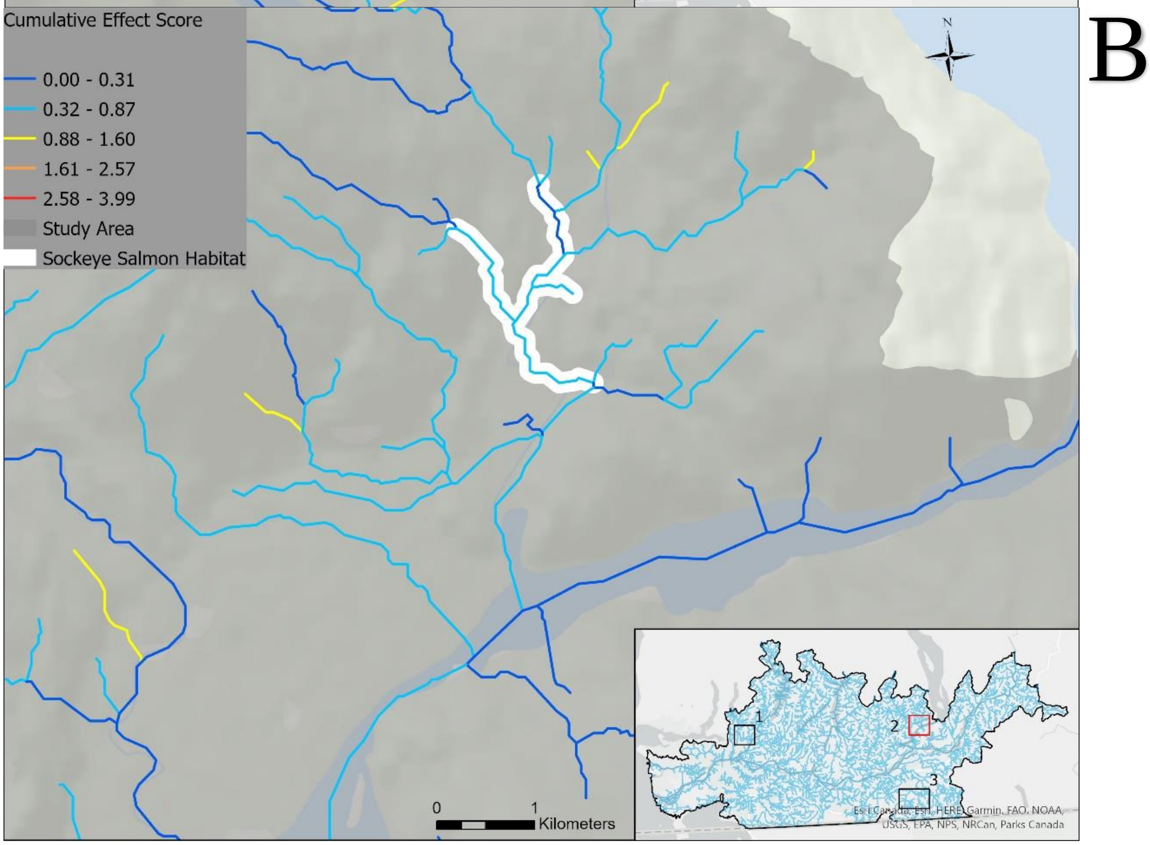


Figure 10. Coastrange Sculpin habitat (white outline) mean cumulative effect scores. The inset shows the location of the habitat patch within the Fraser Valley.


Cumulative Effect Score
0.00 - 0.31
0.32 - 0.87
0.88 - 1.60
1.61 - 2.57
2.58 - 3.99
Study Area
Sockeye Salmon Habitat
N
A
0
1
Kilometers
1
2
3
Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada


Cumulative Effect Score
0.00 - 0.31
0.32 - 0.87
0.88 - 1.60
1.61 - 2.57
2.58 - 3.99
Study Area
Sockeye Salmon Habitat
N
B
0
1
Kilometers
1
2
3
Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada

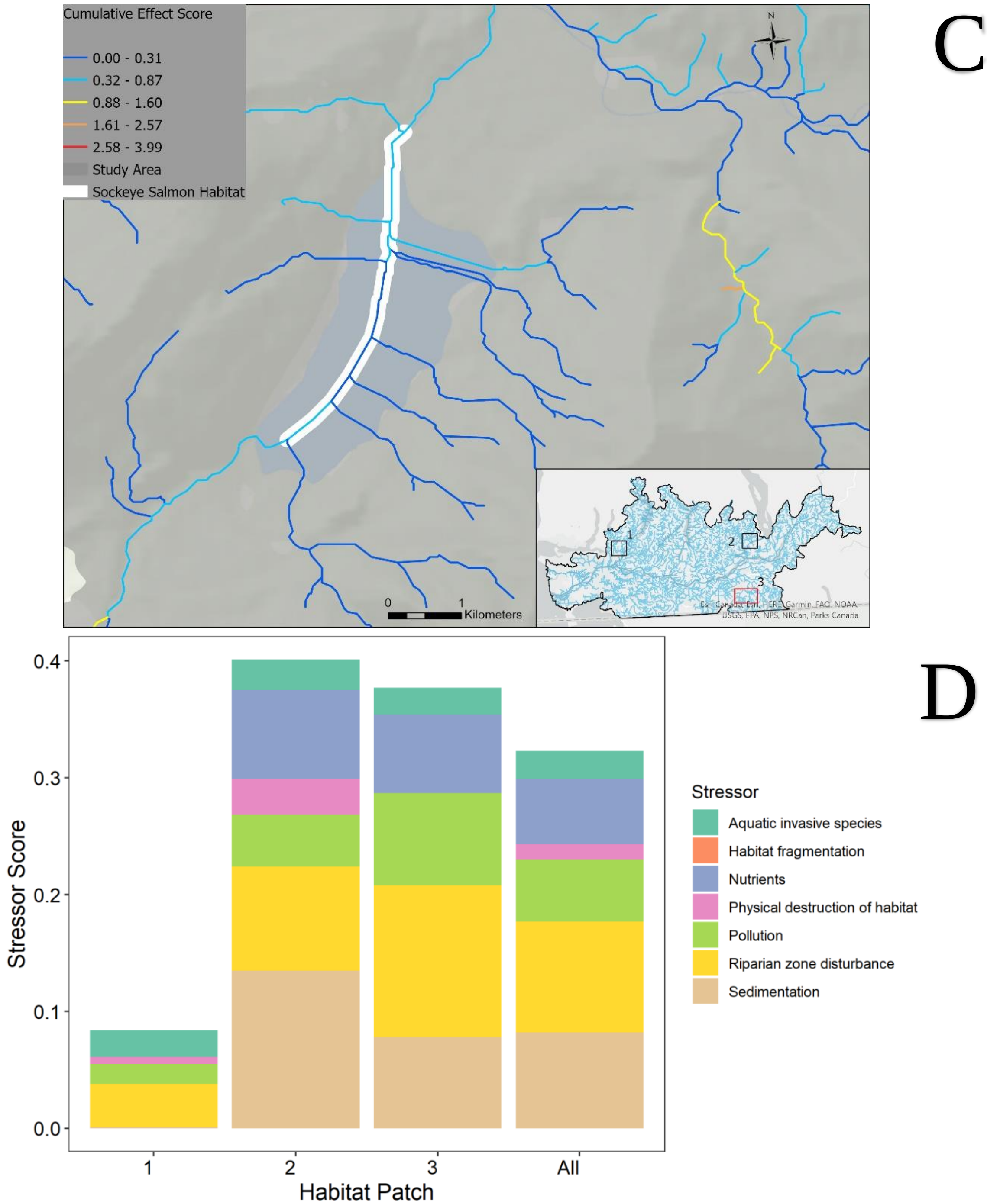


Figure 11. (A-C) Sockeye Salmon discontinuous habitat patches (white outline) mean cumulative effect scores. The inset shows the location of the habitat patch within the Fraser Valley. (D) Stacked mean threat scores for Sockeye Salmon habitat patches. Habitat patches 1-3 mean values are across stream reaches within each patch, and 'all' mean values are across all stream reaches within the species' habitat. The top of the bar represents the mean cumulative effect score.

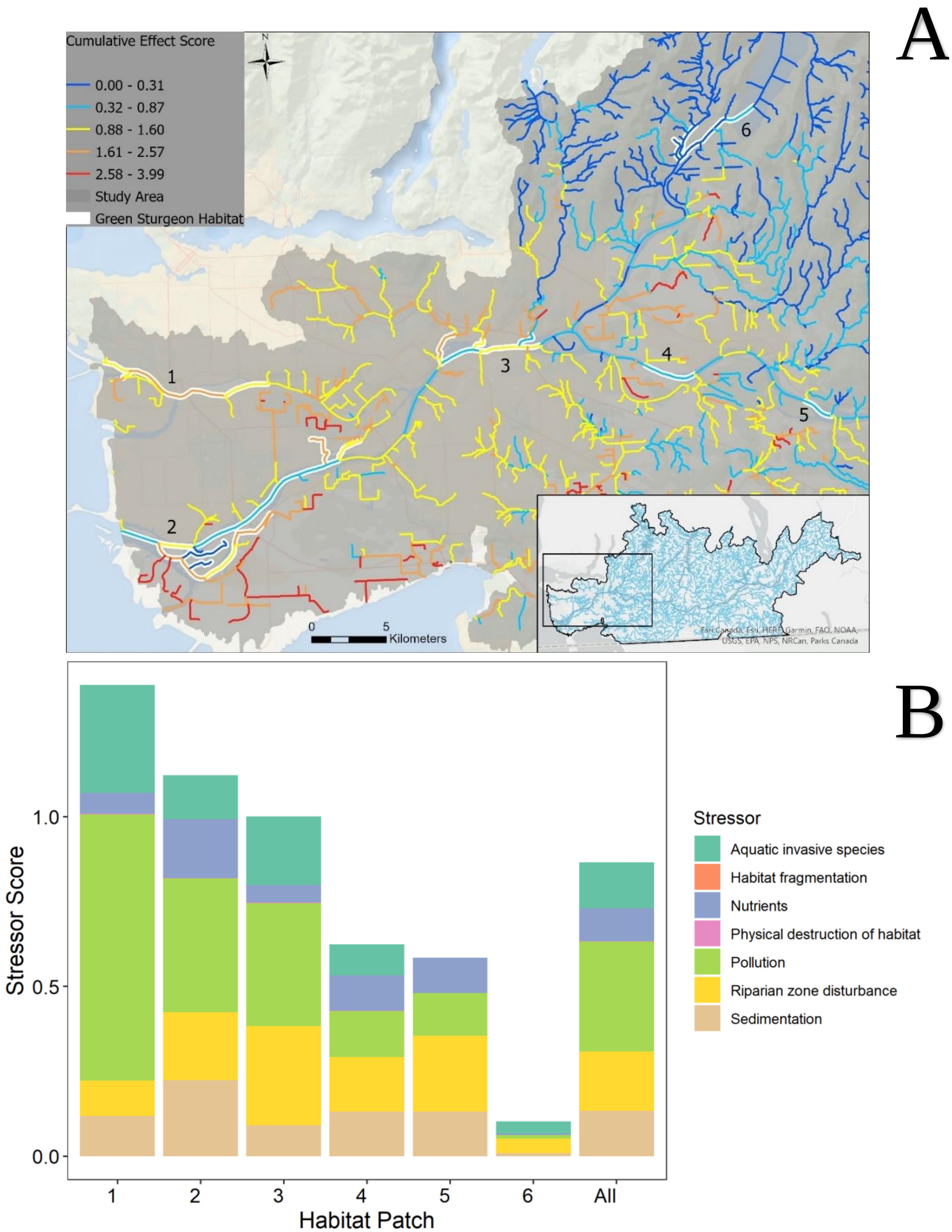
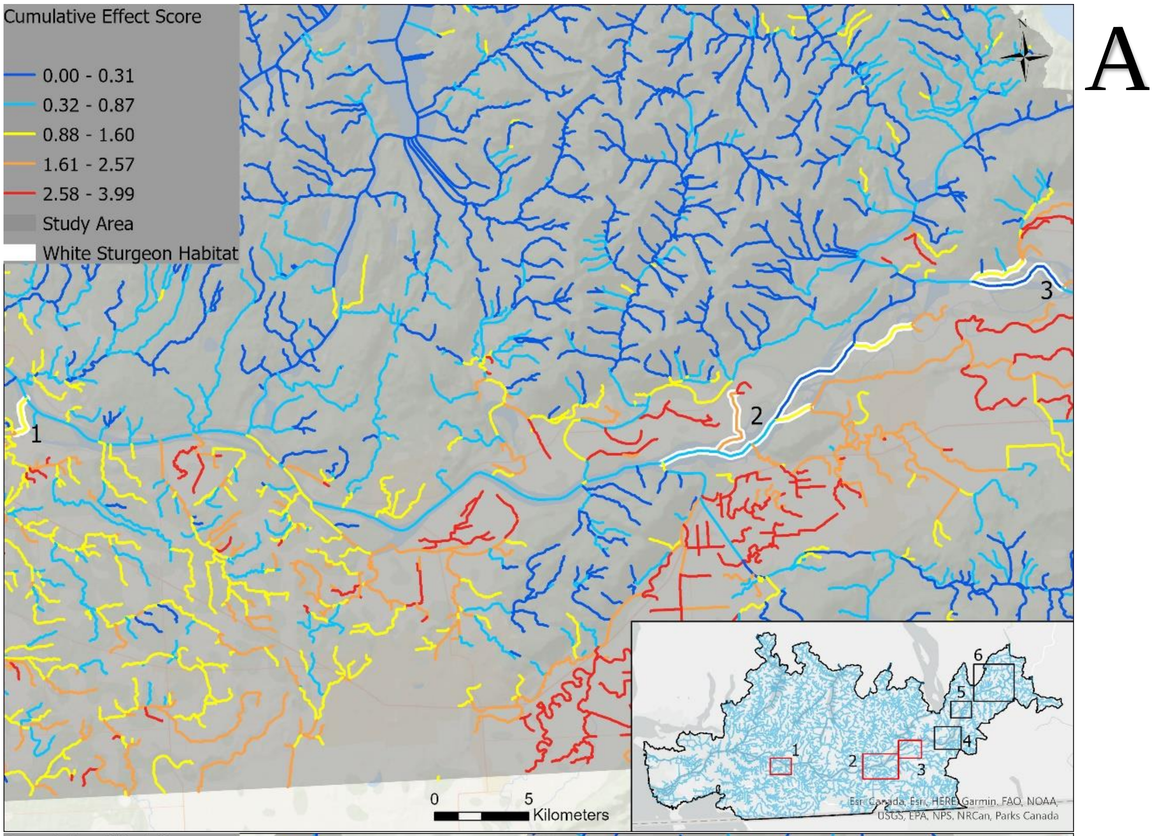
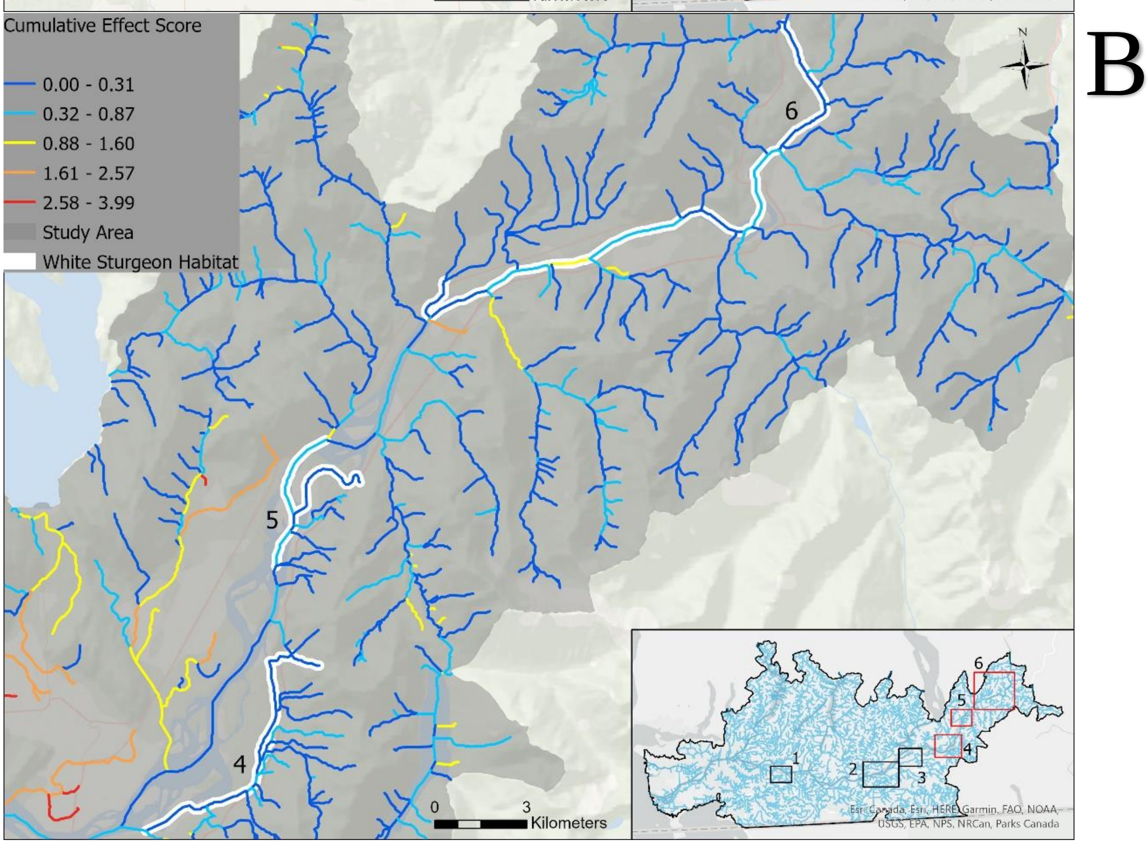


Figure 12. (A) Green Sturgeon discontinuous habitat patches (white outline) mean cumulative effect scores. The inset shows the location of habitat patch within the Fraser Valley. (B) Stacked mean threat scores for Green Sturgeon habitat patches. Habitat patches 1-6 mean values are across stream reaches within each patch, and 'all' mean values are across all stream reaches. The top of the bar represents the mean cumulative effect score.


Cumulative Effect Score
0.00 - 0.31
0.32 - 0.87
0.88 - 1.60
1.61 - 2.57
2.58 - 3.99
Study Area
White Sturgeon Habitat
A
1
2
3
0
5
Kilometers
Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada


Cumulative Effect Score
0.00 - 0.31
0.32 - 0.87
0.88 - 1.60
1.61 - 2.57
2.58 - 3.99
Study Area
White Sturgeon Habitat
B
4
5
6
0
3
Kilometers
Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada

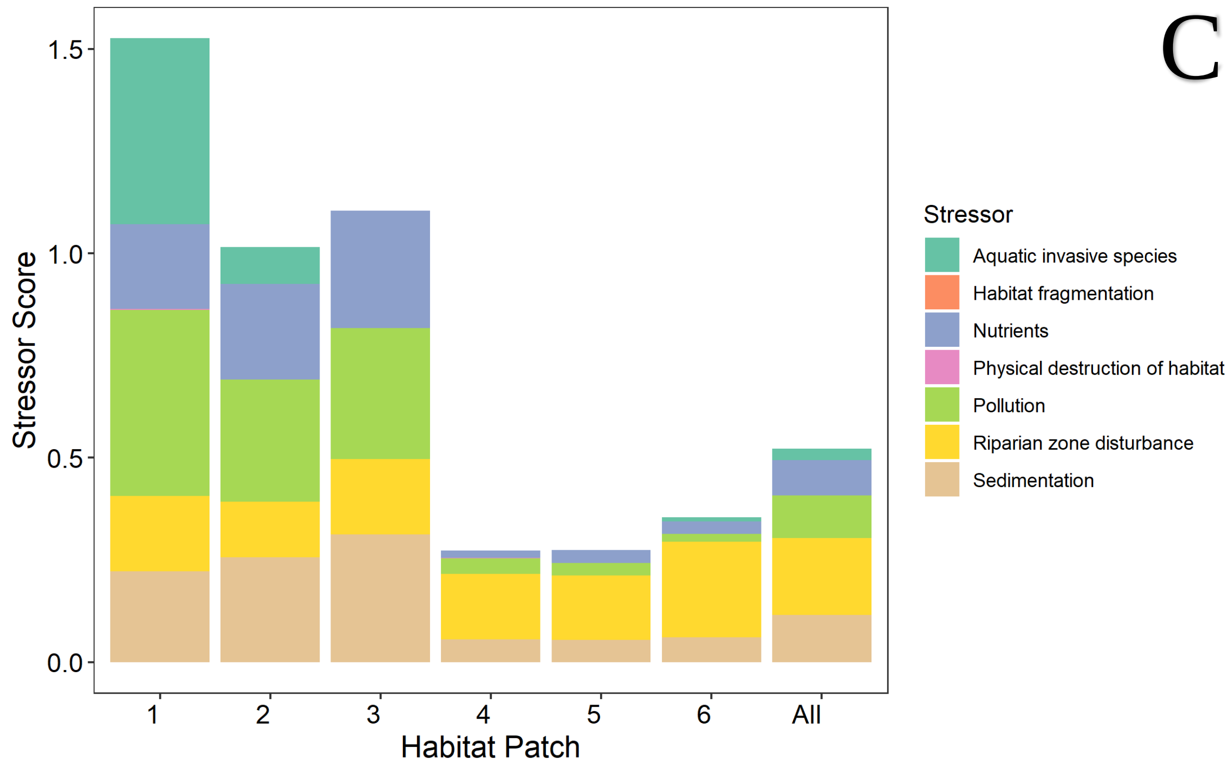
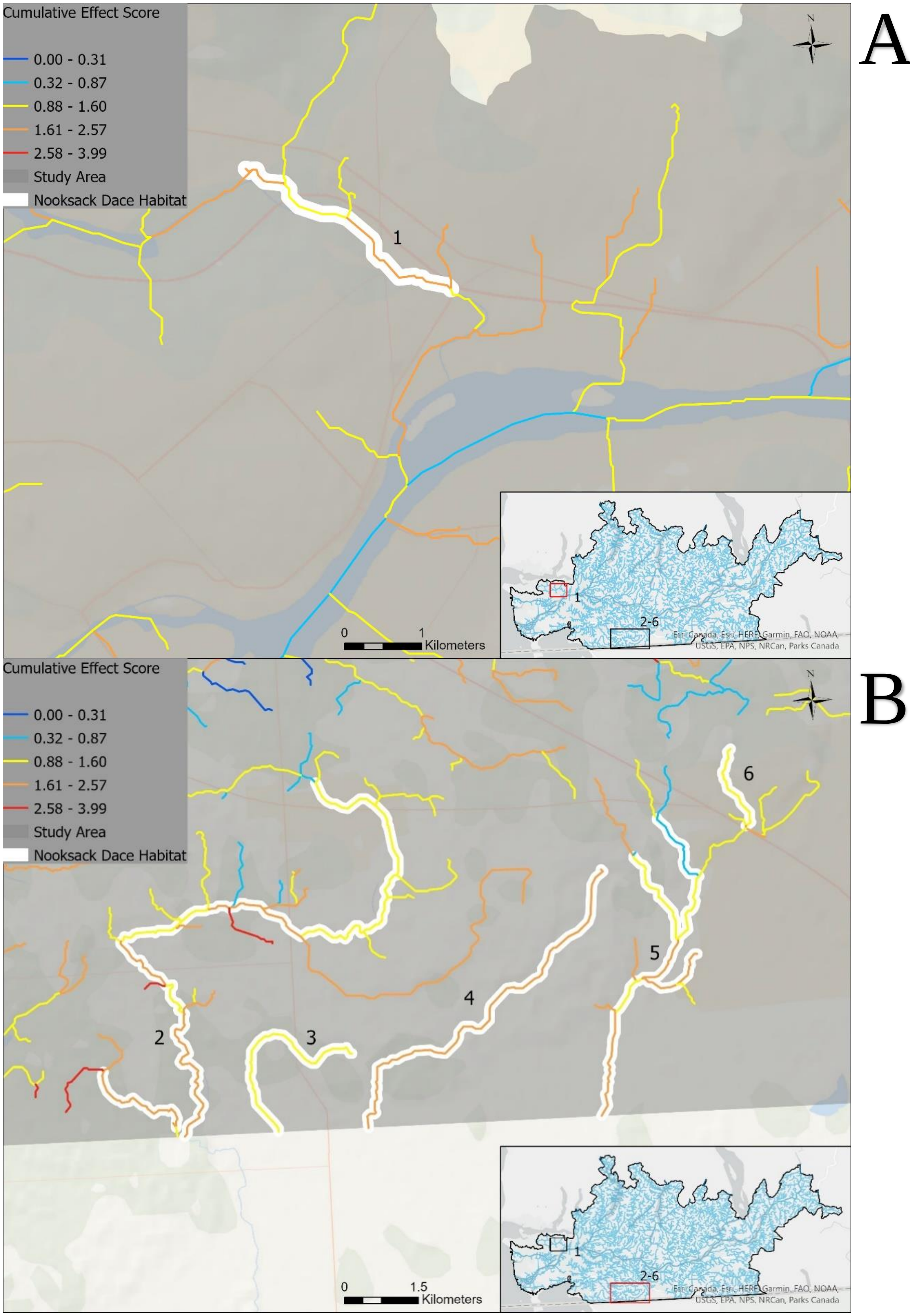


Figure 13. (A-B) White Sturgeon discontinuous habitat patches (white outline) mean cumulative effect scores. The inset shows the location of the habitat patch within the Fraser Valley. (C) Stacked mean threat scores for White Sturgeon habitat patches. Habitat patches 1-6 mean values are across stream reaches within each patch, and 'all' mean values are across all stream reaches within the species' habitat. The top of the bar represents the mean cumulative effect score.


Cumulative Effect Score
0.00 - 0.31
0.32 - 0.87
0.88 - 1.60
1.61 - 2.57
2.58 - 3.99
Study Area
Nooksack Dace Habitat
A
1
0
1
Kilometers
2-6
Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada
Cumulative Effect Score
0.00 - 0.31
0.32 - 0.87
0.88 - 1.60
1.61 - 2.57
2.58 - 3.99
Study Area
Nooksack Dace Habitat
B
2
3
4
5
6
0
1.5
Kilometers
1
2-6
Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada

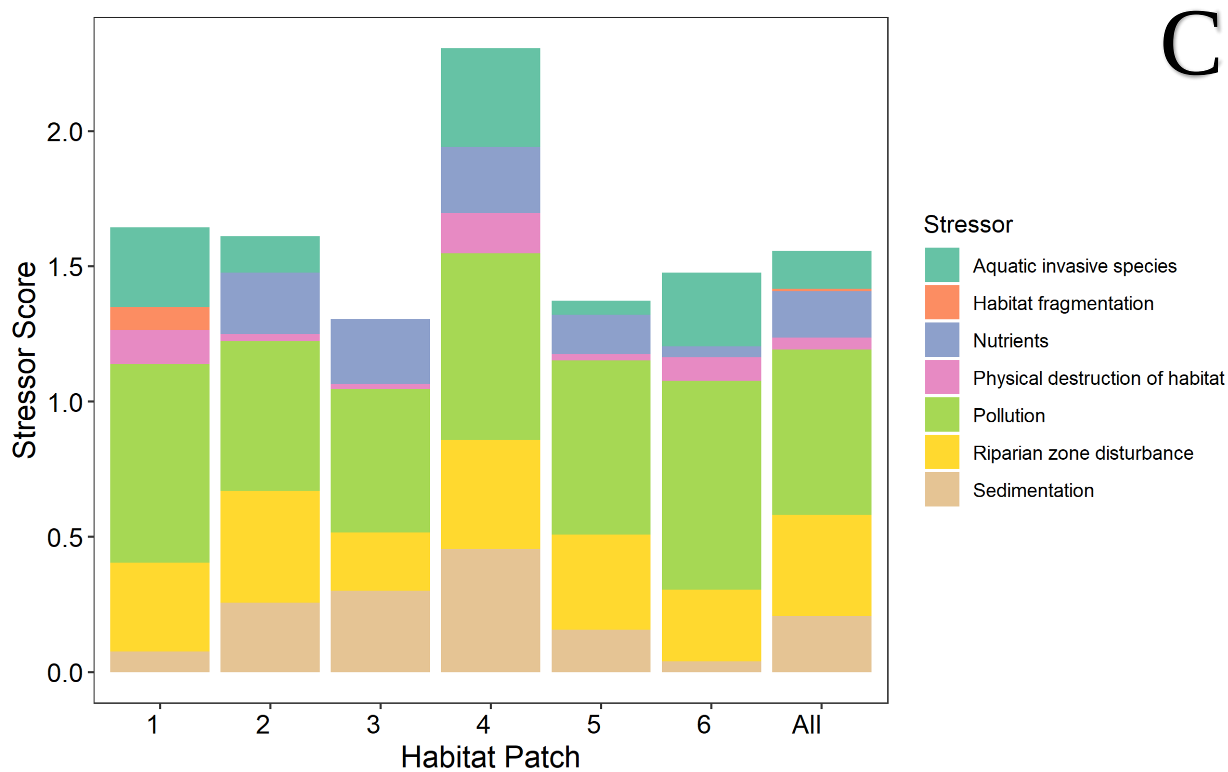
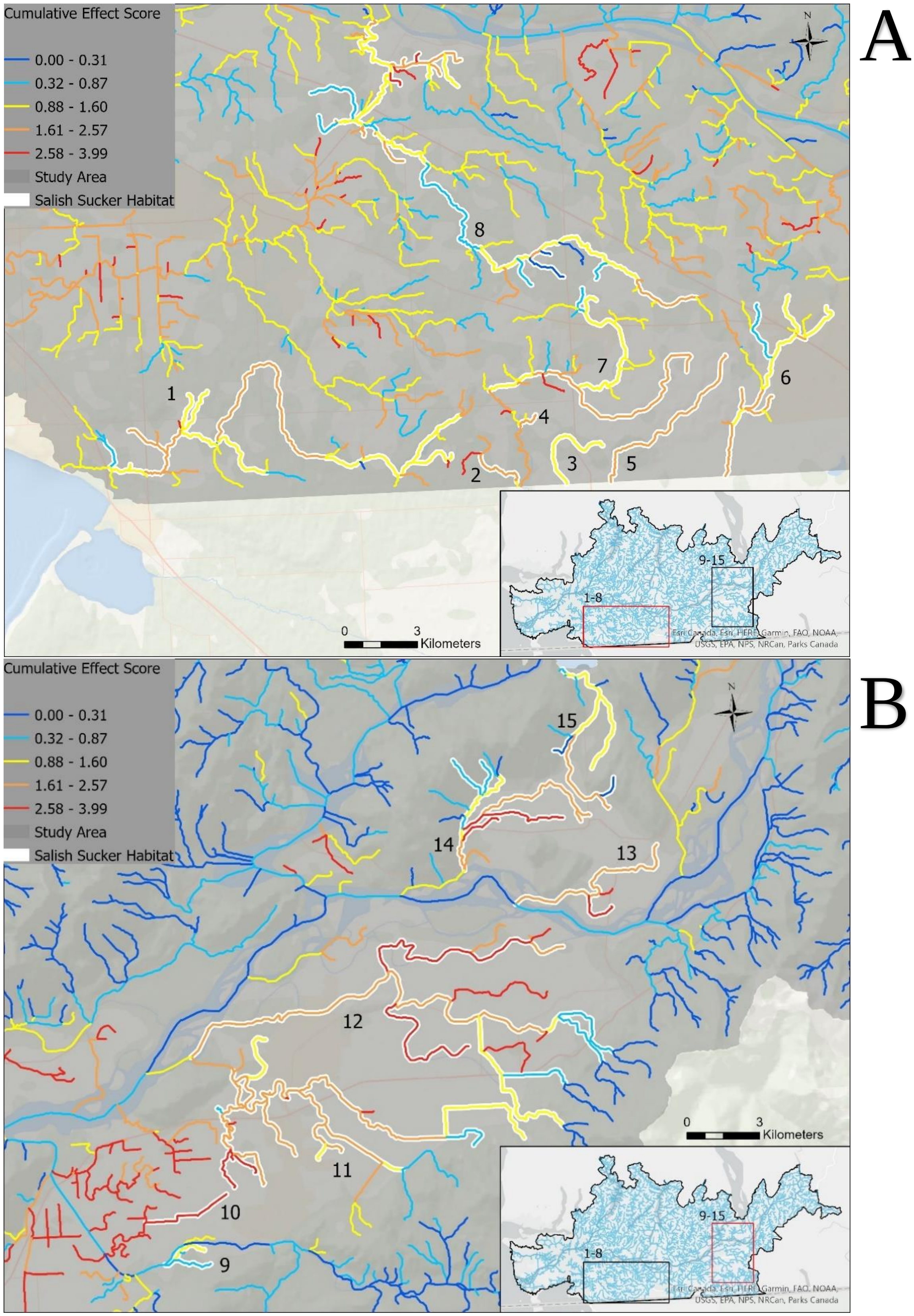


Figure 14. (A-B) Nooksack Dace discontinuous habitat patches (white outline) mean cumulative effect scores. The inset shows the location of habitat patch within the Fraser Valley. (C) Stacked mean threat scores for Nooksack Dace habitat patches. Habitat patches 1-6 mean values are across stream reaches within each patch, and ‘all’ mean values are across all stream reaches within the species’ habitat. The top of the bar represents the mean cumulative effect score.


A
Cumulative Effect Score
0.00 - 0.31
0.32 - 0.87
0.88 - 1.60
1.61 - 2.57
2.58 - 3.99
Study Area
Salish Sucker Habitat
N
1
2
3
4
5
6
7
8
0
3
Kilometers
9-15
1-8
Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada
B
Cumulative Effect Score
0.00 - 0.31
0.32 - 0.87
0.88 - 1.60
1.61 - 2.57
2.58 - 3.99
Study Area
Salish Sucker Habitat
N
9
10
11
12
13
14
15
0
3
Kilometers
9-15
1-8
Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada

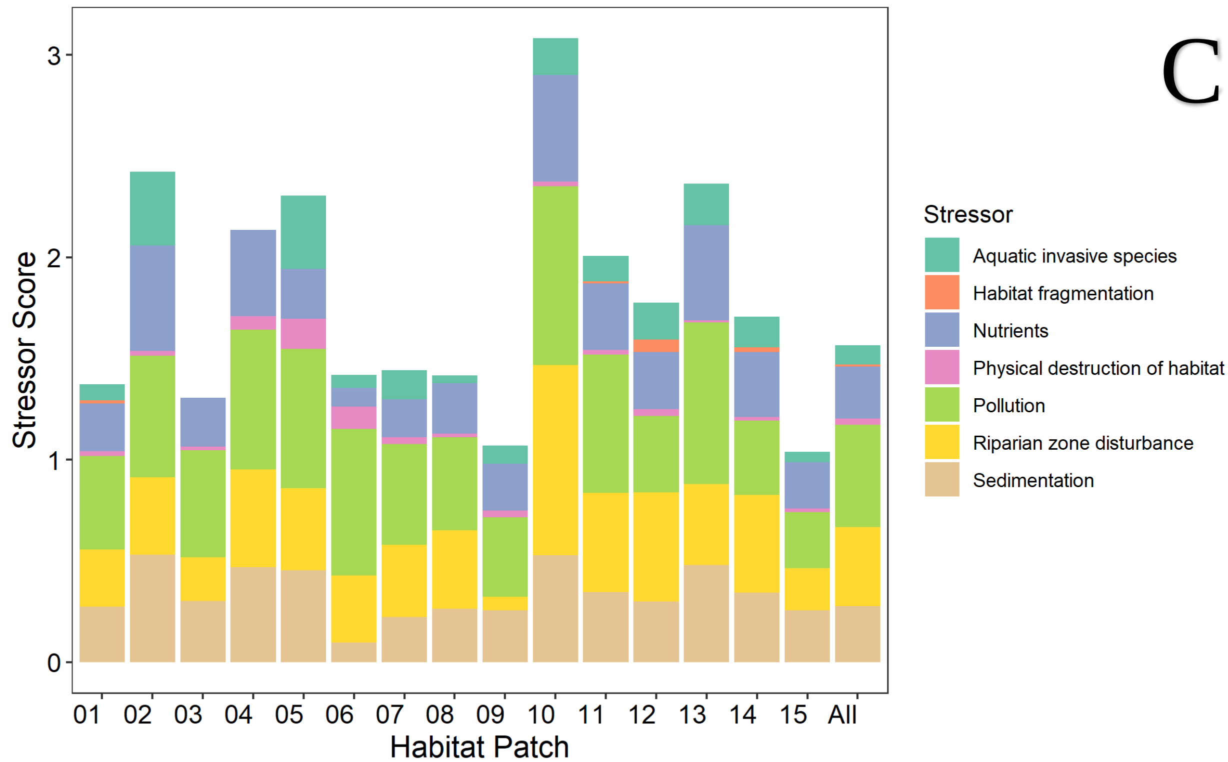


Figure 15. (A-B) Salish Sucker discontinuous habitat patches (white outline) mean cumulative effect scores. The inset shows the location of habitat patch within the Fraser Valley. (C) Stacked mean threat scores for Salish Sucker habitat patches. Habitat patches 1-15 mean values are across stream reaches within each patch, and 'all' mean values are across all stream reaches within the species' habitat. The top of the bar represents the mean cumulative effect score.

DISCUSSION

Our estimated threat and cumulative effect scores showed that landscape disturbance poses significant threat to at-risk fish their habitat, particularly relative to the extent of the Fraser Valley, BC. Stream reaches that were estimated to have the highest threat levels were primarily located within the valley floor and flood plain where there is extensive urbanization and agriculture. The majority habitat for the eight at-risk species habitat was also located within this area, with few of the species except salmon who utilize the less impacted northern, mountainous streams. The finding that cumulative effects were higher within at-risk species habitat than on average across the Fraser Valley was also indicative of why these populations are declining. Pollution and riparian zone disturbance were highlighted as key threats for at-risk species habitat and point to a potential focus for management actions. In addition, maps of cumulative effect scores along the stream network for each species' habitat provide an indication of where restoration resources may be most beneficial.

Salish Sucker and Nooksack Dace had the highest cumulative effect scores within their critical habitat compared to the other six at-risk species, corresponding with their classifications of

Threatened and Endangered (the two highest Species at Risk classes), respectively. The majority of smaller streams where these fish are located are adjacent to dense urban populations and agricultural land. Urban and agricultural land use are primary drivers of multiple threats including sedimentation, nutrients, pollution, and riparian zone disturbance. Stream reaches located within these two land uses are disproportionately at risk of cumulative effects than those located near other land uses such as mines and forestry sites which contributed to fewer threats. Another feature of Salish Sucker and Nooksack Dace habitat patches that exacerbates threats is that they are primarily located in smaller headwater streams, with few upstream connections and smaller catchments. Headwater streams with smaller catchment sizes have little opportunity for dilution of pollutants, nutrients, and sediment. When landscape disturbances are present near headwater streams, these streams receive the initial, highest levels of the threat inputs before they begin to dilute downstream. These two species have relatively small home ranges and are unlikely to expand from their current habitat into other reaches that are less affected by adjacent landscape disturbances (Pearson, 2015). This reinforces the importance of identifying high priority threats, associated landscape disturbances, and locations of high estimated impacts on their habitat to guide restoration and mitigation activities.

Pollution is a major contributing threat across all species and habitats. It was particularly highest in Nooksack Dace, Salish Sucker, and Green Sturgeon habitats. Most landscape disturbances have the potential to contribute pollution to freshwater habitat, particularly agricultural and urban land cover. This threat encompasses a wide variety of pollutants that have different bioavailability and impacts to freshwater species and ecosystems (i.e., heavy metals vs. hormones). Reducing the amount of pollutants going into freshwater habitats can be facilitated by continuing to improve best practices to create large vegetated buffers between pollution sources and freshwater, limiting pollutant concentrations (i.e., fertilizer and pesticide usage), and continuing to improve filtration of water before it returns to water courses (i.e., improving stormwater pathways).

Riparian zone disturbance was another primary contributing threat across all species and habitats. Healthy riparian zones enhance habitats by providing food sources of terrestrial insects and lowering stream temperature, which in turn can help combat effects of eutrophication and hypoxic conditions (Pusey and Arthington, 2003). In addition to these benefits, a healthy, functional riparian zone will help mitigate effects of threats where substances are flushed into the river system such as sedimentation, pollution, and nutrient input. The importance of maintaining a healthy riparian zone is well understood, and many programs for riparian zone preservation and restoration within the Fraser Valley exist (BC MOA, 2011; Lievesley et al., 2017). Our results corroborate the ongoing emphasis on riparian restoration efforts and highlight areas where restoration may be most needed.

Recommendations for Future Cumulative Effect Assessments

We identified research gaps and avenues for improving future evaluations through the process of developing our threat estimations and the cumulative effect assessment. We presented the results of our assessment above as a strong initial step towards a comprehensive cumulative effect assessment methodology for fish and fish habitat as we continue to develop and refine threat estimations for stream networks in British Columbia.

We offer the following suggestions to improve future threat evaluation:

1. Our aquatic invasive species risk scoring methods include some sample bias by using point locations of non-native species associated to stream reaches. These species are likely much more pervasive throughout the landscape than the location where they were sampled. The biology of each non-native species should also be considered in the future. For instance, some may be restricted to lakes or rivers and are more likely to impact particular native species and not others, but we did not make these delineations. Some studies have examined impacts of aquatic invasive species at a regional level (Nowosad and Taylor, 2013; Scott et al., 2016), though specific impacts on at-risk species and their habitat are not currently well known.
2. Habitat fragmentation threat mapping was limited by available barrier spatial data. There are considerably more human-made stream barriers (e.g., impassable culverts, weirs, floodgates) on the landscape that are not accurately represented in currently available spatial inventories. Improving spatial data on barriers to fish passage is ongoing work conducted by the BC province and Canadian Wildlife Federation (S. Norris, pers comm.). Calculation of habitat fragmentation may also be improved by considering area or distance of unfragmented habitat on the landscape (i.e., measuring area of intact habitat units instead of the number of barriers per area).
3. Riparian zone disturbance could be measured using a functional quality based metric instead of a distance value (i.e., biodiversity and health of vegetation species present, or presence of bank stabilizing plants). Studies are also re-evaluating the 30 m benchmark distance for defining the riparian zone (Caskenette et al., 2020). In addition, riparian zone presence and function is linked to most other freshwater threats through bank stabilization and filtration capacities. The presence of a healthy, functioning riparian zone along stream reaches could be incorporated into metrics for decreasing the effects of threats such as sedimentation and pollution at those specific sites.
4. The physical destruction of aquatic habitat threat can be improved with spatial and temporal information on gravel mining activity. Gravel mining is a common occurrence within the Fraser Valley, however data for this activity were not readily available.
5. More complex models for estimating sedimentation have been developed in the Pacific Northwest; however, these rely on extensive *in situ* data for model fitting and validation (Beechie et al., 2021). Without these data, improved approximation of sedimentation risk could include bank slope, distance to water courses, and substrate type variables. Sediment loading has also been shown to be strongly correlated with precipitation and storm pulse events (Demir et al., 2012), which could be incorporated into spatial analyses.
6. As with sediment, the behaviour of nutrients in freshwater systems is very complex. The amount of nutrients flushed into a waterway can be impacted by harvest method, precipitation events, and the vegetation present along stream banks (Pike et al., 2010). During this mapping exercise, waste water discharge areas were mapped as point locations near urban and mine site areas. However, the freshwater system impacts of waste water

discharge is likely much larger than the point location on the landscape. In particular, Environment and Climate Change Canada have developed a spatial mapping tool for the Fraser River basin (Pollutants Affecting Whales and their Prey Inventory Tool [PAWPIT], https://pawpit-oipabp.ca/) that comprehensively estimates point source contaminant releases (i.e., pollutants and nutrients), as well as runoff contributions from different land use categories. This will be incorporated in future cumulative effect assessments for the region.

7. Pollution is also a complex threat to estimate as there are many types of different pollutants that behave differently and have different levels of bioavailability in freshwater systems. For instance, hormone pollutants from urban waste water have very different impacts on fish species than heavy metal pollutants from roadways. This threat could be improved by evaluating pollutant types separately and linking them to their associated landscape disturbances, as well as by accounting for flushing based on precipitation and land permeability (Hall et al., 1998). Contaminant release and land use contribution estimates from the PAWPIT tool will be applied in future iterations.
8. Adding the key water state threats including low stream flow, high water temperature, and hypoxic conditions to this analysis will make the cumulative effect scoring more comprehensive. This work is underway by DFO and collaborative partners (D. Weller, J.C. Iacarella, unpublished data).

Other cumulative effect assessment considerations include the nonlinear and interactive effects of threats. Species and habitat responses to threats are often nonlinear, usually in the form of unimodal or threshold responses. Fish species compositions across watersheds in the Fraser River basin were found to respond nonlinearly to many of the landscape disturbances included in this analysis (Iacarella 2022). For instance, greater changes in fish species compositions occurred at lower levels of riparian disturbance than at higher levels. Modeled nonlinear relationships between threat levels and biological responses can be used to create cumulative effect scores (Iacarella 2022; DFO, 2019). In addition, many cumulative effect assessments treat threats additively owing to limited knowledge of when and how threats interact (Halpern and Fujita, 2013).

The relative importance of different threats to the focal ecological component is also an important consideration in cumulative effect assessments and is often addressed by creating vulnerability weights. These weights are commonly identified through expert elicitation or literature review, or may be modeled if threat response data are available (Iacarella 2022; DFO, 2019). Though the threats included in this analysis were identified as important to at-risk fish species through expert elicitation by COSEWIC, further evaluation of the relative importance of the threats to each species is needed for future assessments. We conducted a preliminary literature review to determine the feasibility of assigning vulnerability weightings using current knowledge for two high priority at-risk species in the region, Nooksack Dace and Salish Sucker. A total of 105 peer-reviewed publications and government reports that discussed one or more of the listed threats for these species were compiled through web-based searches of key words. Of these, only fourteen directly addressed responses of either species to the relevant threats. Threat responses that have been evaluated were seasonal lack of flow, hypoxia, and sedimentation. It could not be concluded from this literature review if any of the threat responses were more detrimental than the others. The majority of other resources available investigated the threats within the Fraser Valley, but did not explicitly address impacts to the two species reviewed. There was also some literature evaluating threat responses of closely related species (Longnose Dace (*Rhinichthys cataractae*) and Longnose Sucker (*Catostomus Catostomus*)) occurring outside of the Fraser Valley. These results identified a key research gap and support the need for more studies investigating species-threat responses. Quantification of the relative importance and type of response (non-linearity) to different threats by at-risk species would improve the accuracy of cumulative effect assessments.

Conclusions for Management

The resulting maps and summary statistics from this cumulative effect assessment can be used by resource managers to identify priority habitat for restoration and protection, and threats that warrant monitoring and mitigation actions. In particular, the threat and cumulative effect maps presented here highlight areas on the landscape that are experiencing considerable effects of anthropogenic pressures. When reviewing proposed works that may impact these areas, managers will be able to see the relative levels of disturbance that already exists for the stream network and determine if adding to that level is suitable. Our results also indicate which species have habitat that is most at risk in the Fraser Valley, which habitat patches are particularly stressed, and which reaches within these habitats have higher threat and cumulative effect scores. This enables prioritization of management efforts at multiple scales. For instance, a manager can use these maps to identify the stream reach of Salish Sucker habitat that is currently the most at risk by adjacent land use and prioritize this area for riparian zone restoration. Further, managers can identify the major threat in that habitat, such as pollution or riparian disturbance, and choose restoration methods to mitigate those particular threats. Since threat and cumulative effect scores were calculated for all stream reaches within the Fraser Valley, any area or habitat of interest can be investigated further. The approach developed here can also be readily applied to a greater extent of BC and to other freshwater species' habitats.

ACKNOWLEDGEMENTS

We would like to acknowledge Dr. Daniel Weller (DFO) for developing the linear hydrologic network layer used in these analyses. White Sturgeon spawning habitat data and mine footprint data were provided by the Province of British Columbia. Valuable feedback was provided by DFO's Species At Risk and Fish and Fish Habitat Protection programs. The Nooksack Dace and Salish Sucker literature was completed with contributions from CoastRange Environmental Ltd. This project was funded in part by DFO's Nature Legacy Program.

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APPENDIX

Table A1. Specific metrics and data layers used to calculate landscape-driven threats for at-risk fish species as identified in COSEWIC status reports. All layers were rasterized to a 25 m resolution raster. Threat layer outputs were evaluated as a proportion of the catchment or scaled from 0 – 1 to create a risk score. Risk scores were summed to determine cumulative effect metrics.

Threat	**Metric**	**Upstream Activity Influence**	**Threat Spatial Data**	**Notes**
Aquatic Invasive Species (AIS)	Non-native species richness per Freshwater Atlas assessment watershed units (1:20,000)	No upstream activity influence	-AIS of British Columbia -Provincial Fish Observation Data -Terrestrial Incidental Data	-Non-native species records taken from Provincial Fish Observation data and Terrestrial Incidental data layers -Combined 3 datasets -Includes fish, reptile, amphibian, aquatic bird, and aquatic plant species
Sedimentation	Create binary raster of sediment sources, flow accumulate, divide raster by catchment area	Upstream activity influence	-Cut blocks -Forestry roads -Gravel roads -Agriculture -Burned areas -Mines	-Created agriculture raster (2015) land cover -Cut blocks: 10 year cutoff for harvested areas (2010 – 2021) -Forestry Roads: all roads included (retired and current); renewed sedimentation occurs when areas are resurfaced, but we do not have that information -Gravel roads: all maintained and unmaintained unpaved roads from the Provincial Digital Road Atlas -Fire: 10 year cutoff for burned areas 2010 – 2021 -Mines: all mines included in provincial digitized orthophoto land cover layer
Riparian zone disturbance	-Create 30m buffer to delineate	No upstream	Urban/impervious surfaces	-Urban and agriculture raster (2015) land cover

	‘riparian zone’ around streams, lakes, and large rivers. -Create binary raster of sources of disturbance within the riparian zone -Create binary raster of disturbed and undisturbed riparian areas	activity influence	-Agriculture -Mines -Paved and unpaved roads -Defoliating pest infestation areas -Burned areas -Cut blocks -Rail lines	-Mines: all mines included in provincial digitized orthophoto land cover layer -All roads from the provincial Digital Road Atlas and forestry roads -Provincial areas of defoliating pest infestations: 10 year cutoff (2010 – 2021); severe and very severe infestation levels -Fire: 10 year cutoff for burned areas 2010 – 2021 -Cut blocks: 10 year cutoff for harvested areas (2010 – 2021)
Nutrients	Create binary raster of nutrient sources, flow accumulate, divide raster by catchment area	Upstream activity influence	-Agriculture land cover -Forest fires -Cut blocks -Waste water discharge areas -Defoliating pest infestation areas	-Created agriculture land cover classes from 2015 land cover layer -Fire: 10 year cutoff for burned areas 2010-2021 -Cut blocks : 10 year cutoff, 2010-2021 -All active waste water discharge areas -Provincial areas of defoliating pest infestations: 10 year cutoff (2010 – 2021); severe and very severe infestation levels
Pollution	Create binary raster of pollution sources, flow accumulate, divide raster by catchment area	Upstream activity influence	-Urban land cover -Agriculture land cover -Paved roads -Mines -Waste water discharge areas	-Created urban and agriculture land cover classes from 2015 land cover layer -Paved roads from provincial Digital Road Atlas -Mines: all mines included in provincial digitized orthophoto land cover layer

				-All active waste water discharge areas
Physical destruction of habitat (Aquatic)	-Identify areas where roads cross streams -Create binary raster of sources of disturbance within aquatic habitat -Create binary raster of disturbed and undisturbed aquatic habitat	No upstream activity influence	-All Roads -Mines -BC Dams	-All roads from the Provincial Digital Road Atlas -Mines: all mines included in provincial digitized orthophoto land cover layer that are within 30 m of water courses
Habitat fragmentation	Calculated on a per species habitat basis. For each species, fragmentation is calculated as the number of barriers present per habitat patch	No upstream activity influence	-BC Dams	

Table A2: Chinook Salmon threat and cumulative effect scores calculated from 11 total stream reaches within one continuous habitat patch.

Habitat Patch	Threat	Min	Max	Mean	SE
1	Nutrients	0.058	0.074	0.063	0.000
	Pollution	0.002	0.020	0.015	0.002
	Sedimentation	0.087	0.112	0.093	0.002
	Physical destruction of habitat	0.000	0.000	0.000	0.000
	Riparian zone disturbance	0.000	0.333	0.127	0.034
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.091	0.017	0.011
	Cumulative effects score	0.164	0.502	0.315	0.035

Table A3: Coastrange Sculpin threat and cumulative effect scores calculated from 8 stream reaches creating one continuous habitat patch.

Habitat Patch	Threat	Min	Max	Mean	SE
1	Nutrients	0.052	0.090	0.067	0.005
	Pollution	0.066	0.099	0.079	0.004
	Sedimentation	0.064	0.010	0.078	0.004
	Physical destruction of habitat	0.000	0.000	0.000	0.000
	Riparian zone disturbance	0.000	0.375	0.130	0.047
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.182	0.023	0.023
	Cumulative effects score	0.224	0.572	0.376	0.046

Table A4: Mountain Sucker threat and cumulative effect scores calculated from 60 stream reaches creating one continuous habitat patch.

Habitat Patch	Threat	Min	Max	Mean	SE
1	Nutrients	0.000	0.544	0.082	0.016
	Pollution	0.006	0.763	0.098	0.022
	Sedimentation	0.002	0.559	0.109	0.015
	Physical destruction of habitat	0.000	0.007	0.000	0.000
	Riparian zone disturbance	0.000	1.000	0.210	0.028
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.364	0.030	0.010
	Cumulative effects score	0.093	2.533	0.529	0.065

Table A5: Sockeye Salmon threat and cumulative effect scores calculated from 19 stream reaches creating three continuous habitat patches.

Habitat Patch	Threat	Min	Max	Mean	SE
All	Nutrients	0.000	0.101	0.056	0.009
	Pollution	0.000	0.111	0.053	0.008
	Sedimentation	0.000	0.152	0.082	0.012
	Physical destruction of habitat	0.000	0.125	0.013	0.000
	Riparian zone disturbance	0.000	0.375	0.095	0.024
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.182	0.024	0.012
	Cumulative effects score	0.002	0.572	0.323	0.038
1	Nutrients	0.000	0.000	0.000	0.000
	Pollution	0.000	0.065	0.017	0.016
	Sedimentation	0.000	0.001	0.001	0.001
	Physical destruction of habitat	0.000	0.023	0.006	0.006
	Riparian zone disturbance	0.000	0.118	0.037	0.028
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.091	0.023	0.023
	Cumulative effects score	0.002	0.206	0.083	0.045
2	Nutrients	0.000	0.101	0.076	0.015
	Pollution	0.028	0.111	0.044	0.012
	Sedimentation	0.098	0.152	0.135	0.009
	Physical destruction of habitat	0.000	0.125	0.031	0.018
	Riparian zone disturbance	0.000	0.191	0.089	0.032
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.091	0.026	0.017

	Cumulative effects score	0.289	0.526	0.401	0.037
3	Nutrients	0.052	0.090	0.067	0.005
	Pollution	0.066	0.099	0.079	0.004
	Sedimentation	0.064	0.010	0.078	0.004
	Physical destruction of habitat	0.000	0.000	0.000	0.000
	Riparian zone disturbance	0.000	0.375	0.130	0.047
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.182	0.023	0.023
	Cumulative effects score	0.224	0.572	0.376	0.046

Table A6: Green Sturgeon threat and cumulative effect scores calculated from 44 stream reaches creating six continuous habitat patches.

Habitat Patch	Threat	Min	Max	Mean	SE
All	Nutrients	0.000	0.364	0.097	0.018
	Pollution	0.000	0.923	0.324	0.050
	Sedimentation	0.000	0.482	0.134	0.022
	Physical destruction of habitat	0.000	0.018	0.001	0.00
	Riparian zone disturbance	0.000	0.857	0.174	0.030
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	1.000	0.136	0.032
	Cumulative effects score	0.002	2.190	0.867	0.100
1	Nutrients	0.051	0.082	0.061	0.007
	Pollution	0.760	0.796	0.784	0.008
	Sedimentation	0.058	0.159	0.119	0.022
	Physical destruction of habitat	0.000	0.004	0.002	0.001
	Riparian zone disturbance	0.029	0.204	0.104	0.043
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	1.000	0.318	0.231
	Cumulative effects score	0.999	2.190	1.388	0.272
2	Nutrients	0.000	0.364	0.174	0.032
	Pollution	0.000	0.791	0.394	0.069
	Sedimentation	0.000	0.482	0.224	0.040
	Physical destruction of habitat	0.000	0.018	0.001	0.001
	Riparian zone disturbance	0.000	0.442	0.200	0.035
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.364	0.129	0.030

	Cumulative effects score	0.091	2.029	1.123	0.146
3	Nutrients	0.000	0.092	0.051	0.015
	Pollution	0.114	0.923	0.363	0.119
	Sedimentation	0.036	0.117	0.091	0.011
	Physical destruction of habitat	0.000	0.008	0.002	0.001
	Riparian zone disturbance	0.000	0.857	0.292	0.108
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.727	0.202	0.094
	Cumulative effects score	0.330	1.857	1.002	0.166
4	Nutrients	0.104	0.104	0.104	0.104
	Pollution	0.136	0.136	0.136	0.136
	Sedimentation	0.131	0.131	0.131	0.131
	Physical destruction of habitat	0.001	0.001	0.001	0.001
	Riparian zone disturbance	0.161	0.161	0.161	0.161
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.091	0.091	0.091	0.091
	Cumulative effects score	0.624	0.624	0.624	0.624
5	Nutrients	0.104	0.104	0.104	0.104
	Pollution	0.126	0.126	0.126	0.126
	Sedimentation	0.131	0.131	0.131	0.131
	Physical destruction of habitat	0.000	0.000	0.000	0.000
	Riparian zone disturbance	0.224	0.224	0.224	0.224
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.000	0.000	0.000
	Cumulative effects score	0.584	0.584	0.584	0.584
6	Nutrients	0.000	0.010	0.005	0.002

Pollution	0.000	0.061	0.010	0.006
Sedimentation	0.000	0.017	0.009	0.003
Physical destruction of habitat	0.000	0.004	0.000	0.000
Riparian zone disturbance	0.000	0.313	0.043	0.031
Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
Aquatic invasive species (scaled)	0.000	0.273	0.036	0.028
Cumulative effects score	0.002	0.612	0.104	0.058

Table A7: White Sturgeon threat and cumulative effect scores calculated from 45 stream reaches creating six continuous habitat patches.

Habitat Patch	Threat	Min	Max	Mean	SE
All	Nutrients	0.000	0.596	0.086	0.020
	Pollution	0.009	0.680	0.105	0.026
	Sedimentation	0.002	0.598	0.115	0.019
	Physical destruction of habitat	0.000	0.007	0.000	0.000
	Riparian zone disturbance	0.000	0.944	0.188	0.031
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive Species (scaled)	0.000	0.455	0.028	0.013
	Cumulative effects score	0.093	2.229	0.523	0.075
1	Nutrients	0.207	0.207	0.207	0.207
	Pollution	0.455	0.455	0.455	0.455
	Sedimentation	0.222	0.222	0.222	0.222
	Physical destruction of habitat	0.002	0.002	0.002	0.002
	Riparian zone disturbance	0.185	0.185	0.185	0.185
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.455	0.455	0.455	0.455
	Cumulative effects score	1.526	1.526	1.526	1.526
2	Nutrients	0.065	0.596	0.234	0.077
	Pollution	0.042	0.680	0.299	0.106
	Sedimentation	0.094	0.598	0.256	0.073
	Physical destruction of habitat	0.000	0.001	0.000	0.001
	Riparian zone disturbance	0.000	0.288	0.136	0.041
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.273	0.091	0.040

	Cumulative effects score	0.239	2.229	1.016	0.270
3	Nutrients	0.053	0.382	0.288	0.079
	Pollution	0.044	0.431	0.320	0.093
	Sedimentation	0.080	0.404	0.312	0.078
	Physical destruction of habitat	0.000	0.000	0.000	0.000
	Riparian zone disturbance	0.056	0.330	0.185	0.062
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.000	0.000	0.000
	Cumulative effects score	0.293	1.499	1.106	0.280
4	Nutrients	0.004	0.044	0.018	0.003
	Pollution	0.016	0.053	0.038	0.003
	Sedimentation	0.014	0.117	0.056	0.008
	Physical destruction of habitat	0.000	0.007	0.001	0.001
	Riparian zone disturbance	0.000	0.571	0.160	0.059
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.000	0.000	0.000
	Cumulative effects score	0.093	0.673	0.273	0.057
5	Nutrients	0.000	0.038	0.031	0.008
	Pollution	0.023	0.063	0.031	0.008
	Sedimentation	0.002	0.067	0.054	0.013
	Physical destruction of habitat	0.000	0.000	0.000	0.000
	Riparian zone disturbance	0.000	0.287	0.158	0.049
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.000	0.000	0.000
	Cumulative effects score	0.128	0.415	0.274	0.053
6	Nutrients	0.020	0.037	0.030	0.001

Pollution	0.009	0.027	0.020	0.002
Sedimentation	0.007	0.078	0.061	0.004
Physical destruction of habitat	0.000	0.004	0.000	0.000
Riparian zone disturbance	0.000	0.944	0.233	0.067
Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
Aquatic invasive species (scaled)	0.000	0.182	0.010	0.010
Cumulative effects score	0.106	1.056	0.354	0.067

Table A8: Nooksack Dace threat and cumulative effect scores calculated from 32 stream reaches creating six continuous habitat patches.

Habitat Patch	Threat	Min	Max	Mean	SE
All	Nutrients	0.000	0.521	0.171	0.021
	Pollution	0.394	0.835	0.612	0.021
	Sedimentation	0.040	0.531	0.207	0.021
	Physical destruction of habitat	0.000	0.333	0.044	0.011
	Riparian zone disturbance	0.000	1.000	0.374	0.051
	Habitat fragmentation (scaled)	0.000	0.667	0.010	0.012
	Aquatic invasive species (scaled)	0.000	0.636	0.139	0.027
	Cumulative effects score	0.764	2.422	1.557	0.075
1	Nutrients	0.000	0.002	0.001	0.001
	Pollution	0.593	0.782	0.733	0.047
	Sedimentation	0.040	0.094	0.077	0.012
	Physical destruction of habitat	0.028	0.333	0.127	0.071
	Riparian zone disturbance	0.092	0.583	0.328	0.133
	Habitat fragmentation (scaled)	0.000	0.333	0.083	0.084
	Aquatic invasive species (scaled)	0.091	0.636	0.295	0.131
	Cumulative effects score	1.351	1.934	1.644	0.119
2	Nutrients	0.086	0.521	0.225	0.026
	Pollution	0.401	0.600	0.554	0.011
	Sedimentation	0.101	0.531	0.257	0.027
	Physical destruction of habitat	0.000	0.091	0.028	0.008
	Riparian zone disturbance	0.000	1.000	0.412	0.083
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.364	0.136	0.031

	Cumulative effects score	1.093	2.422	1.613	0.112
3	Nutrients	0.239	0.239	0.239	0.239
	Pollution	0.530	0.530	0.530	0.530
	Sedimentation	0.301	0.301	0.301	0.301
	Physical destruction of habitat	0.019	0.019	0.019	0.019
	Riparian zone disturbance	0.216	0.216	0.216	0.216
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.000	0.000	0.000
	Cumulative effects score	1.305	1.305	1.305	1.305
4	Nutrients	0.245	0.245	0.245	0.245
	Pollution	0.689	0.689	0.689	0.689
	Sedimentation	0.454	0.454	0.454	0.454
	Physical destruction of habitat	0.149	0.149	0.149	0.149
	Riparian zone disturbance	0.405	0.405	0.405	0.405
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.364	0.364	0.364	0.364
	Cumulative effects score	2.305	2.305	2.305	2.305
5	Nutrients	0.043	0.240	0.147	0.023
	Pollution	0.394	0.835	0.644	0.048
	Sedimentation	0.047	0.245	0.156	0.024
	Physical destruction of habitat	0.000	0.039	0.022	0.006
	Riparian zone disturbance	0.060	0.850	0.353	0.096
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.182	0.051	0.022
	Cumulative effects score	0.764	1.908	1.373	0.140
6	Nutrients	0.040	0.040	0.040	0.040

Pollution	0.772	0.772	0.772	0.772
Sedimentation	0.040	0.040	0.040	0.040
Physical destruction of habitat	0.087	0.087	0.087	0.087
Riparian zone disturbance	0.265	0.265	0.265	0.265
Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
Aquatic invasive species (scaled)	0.273	0.273	0.273	0.273
Cumulative effects score	1.477	1.477	1.477	1.477

Table A9: Salish Sucker threat and cumulative effect scores calculated from 202 stream reaches creating 15 continuous habitat patches.

Habitat Patch	Threat	Min	Max	Mean	SE
All	Nutrients	0.000	0.901	0.256	0.012
	Pollution	0.004	1.000	0.506	0.016
	Sedimentation	0.000	0.909	0.277	0.012
	Physical destruction of habitat	0.000	0.500	0.031	0.004
	Riparian zone disturbance	0.000	1.000	0.390	0.022
	Habitat fragmentation (scaled)	0.000	0.667	0.010	0.005
	Aquatic invasive species (scaled)	0.000	0.818	0.095	0.011
	Cumulative effects score	0.056	3.785	1.566	0.051
1	Nutrients	0.024	0.426	0.238	0.016
	Pollution	0.359	0.678	0.463	0.016
	Sedimentation	0.026	0.442	0.273	0.016
	Physical destruction of habitat	0.000	0.091	0.022	0.005
	Riparian zone disturbance	0.000	0.914	0.283	0.064
	Habitat fragmentation (scaled)	0.000	0.333	0.013	0.013
	Aquatic invasive species (scaled)	0.000	0.818	0.080	0.037
	Cumulative effects score	0.835	2.501	1.372	0.079
2	Nutrients	0.521	0.521	0.521	0.521
	Pollution	0.600	0.600	0.600	0.600
	Sedimentation	0.531	0.531	0.531	0.531
	Physical destruction of habitat	0.023	0.023	0.023	0.023
	Riparian zone disturbance	0.383	0.383	0.383	0.383
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.364	0.364	0.364	0.364

	Cumulative effects score	2.422	2.422	2.422	2.422
3	Nutrients	0.239	0.239	0.239	0.239
	Pollution	0.530	0.530	0.530	0.530
	Sedimentation	0.301	0.301	0.301	0.301
	Physical destruction of habitat	0.019	0.019	0.019	0.019
	Riparian zone disturbance	0.216	0.216	0.216	0.216
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.000	0.000	0.000
	Cumulative effects score	1.305	1.305	1.305	1.305
4	Nutrients	0.368	0.483	0.425	0.057
	Pollution	0.606	0.776	0.691	0.085
	Sedimentation	0.412	0.523	0.468	0.056
	Physical destruction of habitat	0.000	0.136	0.068	0.068
	Riparian zone disturbance	0.483	0.483	0.483	0.000
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.000	0.000	0.000
	Cumulative effects score	1.868	2.402	2.135	0.267
5	Nutrients	0.245	0.245	0.245	0.245
	Pollution	0.689	0.689	0.689	0.689
	Sedimentation	0.454	0.454	0.454	0.454
	Physical destruction of habitat	0.149	0.149	0.149	0.149
	Riparian zone disturbance	0.405	0.405	0.405	0.405
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.364	0.364	0.364	0.364
	Cumulative effects score	2.305	2.305	2.305	2.305
6	Nutrients	0.000	0.364	0.091	0.026

	Pollution	0.333	1.000	0.724	0.041
	Sedimentation	0.000	0.390	0.096	0.027
	Physical destruction of habitat	0.000	0.500	0.110	0.036
	Riparian zone disturbance	0.000	0.850	0.333	0.068
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.273	0.064	0.020
	Cumulative effects score	0.654	2.133	1.420	0.102
7	Nutrients	0.078	0.348	0.189	0.021
	Pollution	0.101	0.584	0.497	0.033
	Sedimentation	0.092	0.401	0.222	0.024
	Physical destruction of habitat	0.000	0.175	0.033	0.012
	Riparian zone disturbance	0.000	1.000	0.358	0.091
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.455	0.142	0.031
	Cumulative effects score	0.500	2.435	1.441	0.137
8	Nutrients	0.000	0.744	0.248	0.019
	Pollution	0.056	0.892	0.458	0.021
	Sedimentation	0.000	0.767	0.263	0.019
	Physical destruction of habitat	0.000	0.143	0.019	0.004
	Riparian zone disturbance	0.000	1.000	0.389	0.046
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.545	0.039	0.012
	Cumulative effects score	0.056	3.459	1.416	0.083
9	Nutrients	0.153	0.328	0.230	0.041
	Pollution	0.241	0.546	0.391	0.068
	Sedimentation	0.202	0.341	0.256	0.032

	Physical destruction of habitat	0.000	0.071	0.035	0.015
	Riparian zone disturbance	0.000	0.228	0.068	0.055
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.273	0.091	0.065
	Cumulative effects score	0.713	1.569	1.070	0.189
10	Nutrients	0.527	0.527	0.527	0.527
	Pollution	0.884	0.884	0.884	0.884
	Sedimentation	0.529	0.529	0.529	0.529
	Physical destruction of habitat	0.021	0.021	0.021	0.021
	Riparian zone disturbance	0.939	0.939	0.939	0.939
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.182	0.182	0.182	0.182
	Cumulative effects score	3.082	3.082	3.082	3.082
11	Nutrients	0.007	0.901	0.328	0.034
	Pollution	0.080	0.982	0.681	0.039
	Sedimentation	0.016	0.909	0.346	0.033
	Physical destruction of habitat	0.000	0.182	0.025	0.007
	Riparian zone disturbance	0.095	1.000	0.491	0.053
	Habitat fragmentation (scaled)	0.000	0.333	0.011	0.011
	Aquatic invasive species (scaled)	0.000	0.545	0.124	0.025
	Cumulative effects score	0.648	3.785	2.007	0.126
12	Nutrients	0.014	0.716	0.283	0.061
	Pollution	0.016	0.874	0.379	0.071
	Sedimentation	0.018	0.717	0.299	0.059
	Physical destruction of habitat	0.000	0.062	0.032	0.005
	Riparian zone disturbance	0.248	0.860	0.539	0.042

	Habitat fragmentation (scaled)	0.000	0.667	0.062	0.045
	Aquatic invasive species (scaled)	0.000	0.818	0.182	0.061
	Cumulative effects score	0.558	3.191	1.774	0.219
13	Nutrients	0.275	0.710	0.469	0.090
	Pollution	0.722	0.855	0.798	0.034
	Sedimentation	0.293	0.711	0.479	0.087
	Physical destruction of habitat	0.000	0.040	0.010	0.010
	Riparian zone disturbance	0.143	0.565	0.402	0.093
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000
	Aquatic invasive species (scaled)	0.000	0.364	0.205	0.078
	Cumulative effects score	2.005	3.113	2.364	0.253
14	Nutrients	0.085	0.742	0.322	0.059
	Pollution	0.004	0.852	0.369	0.076
	Sedimentation	0.103	0.743	0.342	0.056
	Physical destruction of habitat	0.000	0.091	0.017	0.006
	Riparian zone disturbance	0.000	1.000	0.483	0.086
	Habitat fragmentation (scaled)	0.000	0.333	0.022	0.022
	Aquatic invasive species (scaled)	0.000	0.273	0.152	0.021
	Cumulative effects score	0.486	3.523	1.707	0.264
15	Nutrients	0.019	0.388	0.231	0.037
	Pollution	0.014	0.521	0.276	0.055
	Sedimentation	0.019	0.403	0.255	0.035
	Physical destruction of habitat	0.000	0.067	0.018	0.006
	Riparian zone disturbance	0.000	0.870	0.209	0.089
	Habitat fragmentation (scaled)	0.000	0.000	0.000	0.000

Aquatic invasive species (scaled)	0.000	0.182	0.050	0.023
Cumulative effects score	0.188	2.181	1.038	0.196