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Coastwide Evaluation and Classification of Pacific Region Estuaries based on Anthropogenic Activities and Significant Fish Habitat

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Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Estuaries are highly productive and diverse ecosystems that represent a geographic bottleneck between marine and freshwater systems. Estuaries have been identified as ecologically and biologically significant areas (EBSAs) in Canada's Pacific Region because of their importance for the aggregation, productivity, and fitness of anadromous fishes, including Pacific salmon. However, estuaries are also the site of many anthropogenic activities, and the degradation of estuarine habitats such as eelgrass beds has had corresponding impacts on many species of ecological, economic, and cultural importance. To support a regional request for information to aid integrated coastal planning, a coastwide classification of estuaries based on anthropogenic activities was completed. Anthropogenic activities and associated stressors relevant to estuary habitats were identified through a literature review and used to guide the compilation of spatial datasets. The spatial datasets were then used in a cluster analysis that identified estuaries that share similar activity types and levels of use. Ecological information was then compiled and mapped to highlight how estuarine fishes and fish habitats considered significant or sensitive relate to the results of the clustering analysis and individual estuaries. This broad-scale analysis represents an initial assessment of British Columbia's estuaries that can help guide localized efforts and identify opportunities for management efficiencies among estuaries that face similar activities and stressors. Research needs for future evaluations at a finer-scale scale are detailed, as are linkages with projects underway within specific estuaries, to highlight opportunities for collaboration as priority estuaries are identified for management and conservation action.

ACRONYMS

BC	British Columbia
BCMCA	British Columbia Marine Conservation Analysis
CBD	Convention on Biological Diversity
CHS	Canadian Hydrographic Service
CU	Conservation Unit
DFO	Fisheries and Oceans Canada (formerly Department of Fisheries and Oceans)
EBSA	Ecologically and Biologically Significant Areas
EBM	Ecosystem-based Management
ECCC	Environment and Climate Change Canada
ENSO	El Niño and the Southern Oscillation
ESA	Ecologically Significant Area
ESS	Ecologically Significant Species
FFHPP	Fish and Fish Habitat Protection Program
FREMP	Fraser River Estuary Management Program
MPA	Marine Protected Area
MSP	Marine Spatial Planning
NSB	Northern Shelf Bioregion
NuSEDS	New Salmon Escapement Database System
PAH	Polycyclic Aromatic Hydrocarbon
PBHJV	Pacific Birds Habitat Joint Venture
PECP	Pacific Estuary Conservation Program
RCP	Representative Concentration Pathway
SARA	*Species At Risk Act*
SDM	Species Distribution Model
SeBA	Sensitive Benthic Area
SiBA	Significant Benthic Area
SLR	Sea Level Rise
SOG	Strait of Georgia
TRIM	Terrain Resource Information Management
WSP	Wild Salmon Policy

1. INTRODUCTION

1.1. CONTEXT/BACKGROUND

In the Pacific Region of Canada, estuaries comprise only 3% of the British Columbia (BC) coastline (Figure 1), but their productivity and habitat diversity are of immense importance for a variety of species (Ryder et al. 2007). Estuaries are a geographic bottleneck between terrestrial and marine ecosystems, commonly defined as a “semi-enclosed body of water with a free connection to the open sea where the seawater is measurably diluted with fresh water derived from land drainages” (Pritchard 1967). With their location at the mouths of streams and rivers, estuaries are heavily influenced by freshwater inflow which, together with ocean upwelling patterns and tidal cycles, influence estuary circulation (Geyer and Farmer 1989; Davis et al. 2014) and gradients in salinity, temperature, and dissolved oxygen levels (Quinn 2018). Nutrients delivered from rivers, marine sources, or derived from detrital decomposition (Naiman and Sibert 1979) contribute to the high benthic and pelagic productivity of estuaries (Cloern et al. 2014; Moore et al. 2015; Harfmann et al. 2019). Nutrients and sediments from upstream also increase turbidity, particularly when river flows are high (Semmens 2008; Dashtgard et al. 2012). These complex and dynamic conditions support a wide diversity of habitat types, including eelgrass beds, salt marshes, tidal marshes, sand flats, mud flats, channels, and wetlands (Levings 2016) and, in turn, make estuaries an important nursery environment for juvenile fish such as Pacific salmon (Semmens 2008; Moore et al. 2016). However, estuaries are also the location of many anthropogenic activities, and the fish species and habitats face multiple stressors or threats, including habitat degradation and modification, pollution, invasive species, overexploitation of fish, and climate change (DFO 2019a). A global study of estuaries and coastal seas found that anthropogenic activities have resulted in large decreases in seagrass and wetland habitats within estuaries and that over 90% of the historical abundance of species considered commercially, structurally, or functionally important have been depleted (Lotze et al. 2006).

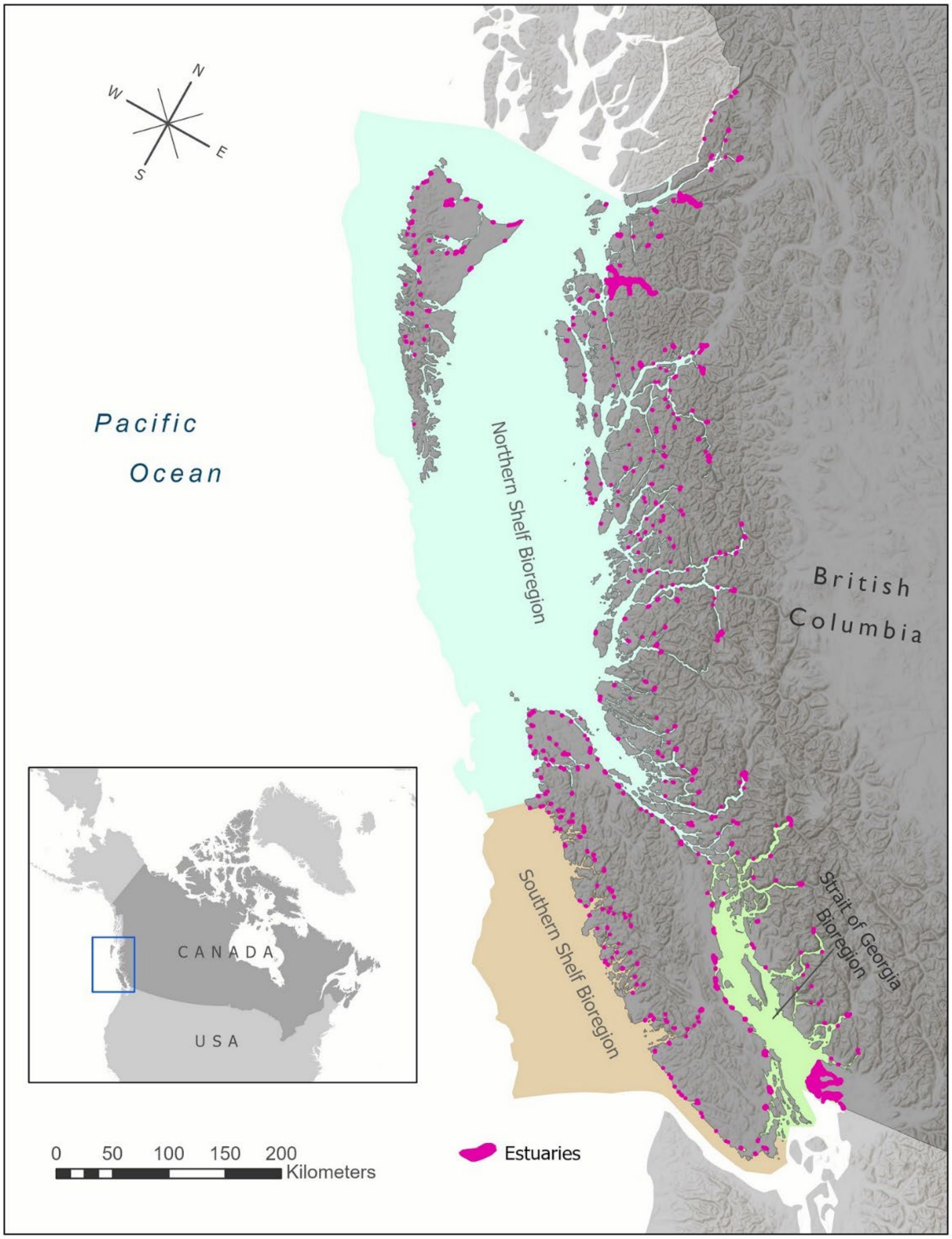

Figure 1. Estuaries and DFO marine bioregions along the BC coast in Canada's Pacific Region. The Offshore Pacific bioregion is not shown. Estuary sizes are exaggerated for visualization purposes.

Human activities and their impacts to estuarine environments and the species they support have been previously assessed in the Pacific Region (e.g., Robb 2014; Hodgson et al. 2020). Building on this previous research, a broad scale coastwide classification of estuaries based on anthropogenic activities has been identified as a regional need to support management decision making. Canada's *Oceans Act* (Government of Canada 1996) provides the legislative framework for an integrated approach to managing Canada's estuarine, coastal, and marine waters and the associated Oceans Strategy (DFO 2002) sets out the objective of developing integrated management plans led by Fisheries and Oceans Canada (DFO). Recent updates to

Canada's *Fisheries Act* (Government of Canada 2019) also highlight the importance of fish habitat. Within DFO, the Fish and Fish Habitat Protection Program (FFHPP) is tasked with estuary and coastal management planning for fish and fish habitat.

The FFHPP has requested that Science Branch develop a coastwide evaluation of Pacific Region estuaries for management and conservation based on the activities that may threaten fish and fish habitat. Given that they may originate in marine, estuarine, and terrestrial areas, all activities were considered relevant to the assessment, regardless of management jurisdiction. Additionally, the FFHPP request includes the need for a better understanding of the importance of individual estuaries to salmon, other significant fish species (e.g., Pacific Herring), and the presence of sensitive fish habitat (e.g., eelgrass). The purpose of this Research Document is to provide a starting point to address this management need and:

1. Review and map current anthropogenic activities in Pacific Region estuaries;
2. Use available data to map significant fish species distributions and sensitive fish habitat within Pacific Region estuaries;
3. Classify estuaries based on common stressors associated with human activities; and
4. Highlight estuaries that are particularly important for key fish species and sensitive fish habitat.

1.1.1. Estuarine Environment

BC estuaries encompass a range of morphologies (Emmett et al. 2000), from estuaries found at the head of fjords, such as the Somass estuary in Alberni Inlet, to those surrounded by expansive deltas and floodplains, such as the Fraser estuary. Estuary morphology can influence the diversity of estuarine habitats and associated fish assemblages. Estuaries with deeper or wider mouths may facilitate greater access to marine species and those with larger zones of high salinity correspond to a broader range of habitat types (Monaco et al. 1992). Estuaries also drain watersheds of different sizes and varying freshwater discharges. Most estuaries along the BC coast are associated with smaller coastal watersheds while the large Fraser River watershed is associated with high freshwater inflow (Emmett et al. 2000). Rivers and streams flowing through estuaries on Haida Gwaii and Vancouver Island tend to be pluvial, with higher flows in winter, while the rivers flowing through mainland estuaries (e.g., Fraser estuary) are often driven by snow melt, with potential peak flows in spring (Hernández-Henriquez et al. 2017). The dynamic physical conditions (e.g., turbidity, salinity, temperature) that support estuarine species and habitats are influenced by many environmental drivers, including freshwater inflow. Sediment input from rivers influences estuary morphology (e.g., extent of mudflats), reduces light penetration and slows plant growth when turbidity levels are high. High turbidity areas also provide habitat and refuge for young salmon by limiting water visibility for predators and reducing predation risk (Gregory and Levings 1998; Sharpe et al. 2019). Nutrients delivered from rivers and marine sources, coupled with in situ detrital decomposition (Naiman and Sibert 1979) result in elevated levels of benthic and pelagic primary production (Moore et al. 2015), which in turn support high densities of fishes and invertebrates. Temporal fluctuations in salinity occur over daily, yearly, and multi-year cycles. Temperature and salinity within an estuary also vary spatially depending on location within the estuary, river flow rates, tides, depth, and circulation patterns, all of which can influence the estuarine flora and fauna. For example, infaunal diversity and density has been shown to decrease with decreasing salinity (Dashtgard et al. 2012), and salinity gradients have been shown to influence the composition of fish species utilizing different eelgrass patches (Robinson et al. 2011). Circulation patterns also contribute to high productivity within estuaries. Freshwater input from rivers coupled with upwelling from deep offshore waters results in the circular flow with freshwater flowing seaward and nutrient-rich water from ocean upwelling moving along the seafloor towards the estuary mouth, leading to high nutrient levels and productivity (Davis et al. 2014). Temporal and spatial variability in salinity, circulation, and currents is also affected by tidal cycles.

1.1.2. Estuarine Species and Habitats

Canada's *Fisheries Act* defines fish habitat as "water frequented by fish and any other areas on which fish depend directly or indirectly to carry out their life processes, including spawning grounds and nursery, rearing, food supply and migration areas" (Government of Canada 2019). Estuaries are known to be important for a variety of fish and invertebrate species of commercial, ecological, and cultural importance, including Pacific salmon and forage fish such as Pacific Herring and Surf Smelt—species that function as important links between low and high trophic levels in the ecosystem (Toft et al. 2018).

Estuaries along the BC coast support important and sensitive fish habitats, including eelgrass beds, macroalgae, marshes, sand flats, mud flats, gravel bars, areas of high turbidity, reefs, and channels. In particular, juvenile salmon are typically thought to use eelgrass, macroalgae, and marsh habitats for foraging and shelter from predation (Thorpe 1994), though this can vary by species and be based on local conditions. For example, Sharpe et al. (2019) observed Chinook and Sockeye more frequently within eelgrass, and Coho within areas with macroalgae. Quinn (2018) points to the use of freshwater areas by Chinook, Coho, and Chum; marsh habitats by Chinook and Chum; sandy beaches, eelgrass beds, mudflats, and channels by Chum and Pink; gravel and cobble beaches by Coho; and open-water habitats by Chinook, Chum, and Pink Salmon. Estuaries are also important transition zones used by anadromous species, such as salmon, to acclimate to changes in salinity as they migrate between freshwater and marine environments (Levings 2016). Temporal variation in habitat use also occurs. Over their residency within an estuary, juvenile salmon may also progressively move from inner estuarine habitats towards the outer reaches where salinity is higher (Quinn 2018). Within the Nanaimo River estuary, Chinook and Chum have been documented using multiple habitat types: the outer reaches of the estuary and within marsh habitats at high tides, and channels and sand flats at lower tides (Healey 1980).

The abundance of biogenic habitat and high productivity within estuaries contribute to their importance as a nursery habitat for juvenile salmon, as well as for other nearshore fishes (Levings 2016; Toft et al. 2018). Growth within estuaries can contribute to improved marine survival for salmon (Duffy and Beauchamp 2011; Weitkamp et al. 2015). As nursery habitat, seagrass habitat supports high juvenile fish and invertebrate growth (by providing better food sources) and density, particularly in temperate regions (McDevitt et al. 2016). A recent evaluation of nursery habitats within 303 estuaries along the Pacific coast of the United States focused on 15 species known to use estuarine habitats as juveniles (Hughes et al. 2014). The study determined that nursery habitat is broadly distributed across the coast, has high commercial, cultural, or ecological importance, and represents and supports a diversity of taxonomic groups (Hughes et al. 2014). The fishes studied included many found in BC estuaries, such as Green Sturgeon, Chinook Salmon, Coho Salmon, Steelhead, English Sole, Starry Flounder, Staghorn Sculpin, Shiner Perch, and Pacific Herring. The authors reviewed the length of estuarine residence and habitat preferences of each species and found that seagrass beds were the habitat used by the most species, though acknowledged their study was biased towards commercial species and more information was needed on non-commercial species that play an important role in estuarine food webs (Hughes et al. 2014). The study also highlighted that small estuaries were found to provide juvenile habitat and recommended regional approaches to future assessments to ensure that the relative contribution of all estuaries can be assessed (Hughes et al. 2014).

In the Fraser River, Chalifour et al. (2019) found that eelgrass habitat supported the greatest number of species, but also found that the majority of salmon were caught in saltmarsh habitat. The study highlights the importance of both species-specific habitat use and a connected habitat mosaic in supporting nearshore fish communities. Additionally, a rich mosaic of connected habitats is crucial in supporting the nursery function of estuaries (Nagelkerken et al. 2015; Seitz et al. 2020). In the Koeye River estuary, Seitz et al. (2020) found that fish, size, abundance, and community structure varied across habitats within the estuary. The variation and distribution of prey species within an estuary is related to the distribution and abundance of habitats and physical conditions (e.g., salinity) within an estuary (Arbeider et al. 2019), which in turn affects habitat use by predators. Proudfoot et al. (2023) also showed the importance in seascape variables such as eelgrass meadow area and edge habitat heterogeneity for eelgrass fish diversity. The diversity of habitats used by Pacific salmon, not just within estuaries but also in connected freshwater and marine environments, increases the challenges associated with management planning (Flitcroft et al. 2019) but are critical for the maintenance of wild salmon populations (Holtby and Ciruna 2007; Stalberg et al. 2009). As mentioned above, mosaic of habitat types are needed to support nearshore fish communities, including Pacific salmon (Weitkamp et al. 2014; Chalifour et al. 2019) as well as other estuarine species such as English Sole (Toft et al. 2018), Shiner Perch, and Three-spined Stickleback (Chalifour et al. 2019). In addition to supporting fish and fish habitat, estuaries are also important habitat for resident and migratory birds and marine mammals. Invertebrate populations are important contributors to estuarine food webs and may influence the habitat preferences of estuarine fish (Arbeider et al. 2019). Dungeness Crabs use estuaries as rearing and nursery habitat (Rooper et al. 2002; Rubidge et al. 2020), with higher densities found in higher salinity areas near the estuary mouth and intertidal flats with ample cover (e.g., macroalgae, eelgrass) that provide protection and high prey density (Rooper et al. 2002). Dungeness Crabs have been observed year-round in the Skeena estuary, in particularly high abundance in eelgrass beds such as those at Flora Bank (Sharpe et al. 2021). Estuaries also provide habitat for filter feeding invertebrates such as clams, Olympia Oyster, and burrowing shrimp (e.g., Blue Mud Shrimp) that feed on suspended detritus, phytoplankton, and zooplankton from the water column (Gillespie 2009; Jeffery et al. 2023). Research into the diets of fish within the Skeena estuary has shown the diets of juvenile Sockeye Salmon to be composed of harpacticoid copepods, while Pacific Herring and Surf Smelt consumed calanoid copepods, and Coho Salmon diets included larval fish (Arbeider et al. 2019; Sharpe et al. 2019). Macrodetritus and filter feeding invertebrates are also food for many other estuary species (Dumbault et al. 2008; Maier and Simenstad 2009). Estuaries provide an abundance of vegetation and invertebrate prey resources for many waterfowl, and crucial staging habitat for migratory bird species. Marine mammals such as Harbour Seals and River Otters also forage extensively in productive estuarine waters (Grigg et al. 2012; Luxa and Acevedo-Gutiérrez 2013; Allegue et al. 2020; Cosby and Szykman Gunther 2021).

1.1.2.1. Ecologically significant species

While the *Fisheries Act* (Government of Canada 2019) provides guidance on the definition of fish habitat, significant fish species and significant or sensitive fish habitat are not similarly defined. However, science guidance provides more information to help us define those ecological features relevant to this science advice request.

Significant fish species can be identified based on the criteria for Ecologically Significant Species (ESS) and community properties established by DFO (Rice 2006; DFO 2006). ESS are species of particularly high ecological importance that exhibit a “controlling influence over key aspects of ecosystem structure and function” (DFO 2006). Species considered ESS include keystone species or highly influential predators, key forage species, nutrient importers or exporters, and habitat-forming species. It is anticipated that, if these species are disturbed, there are greater ecological consequences for the surrounding ecosystem and, as such, enhanced management measures are warranted (DFO 2006).

In the Pacific Region, a large suite of marine and coastal species was assessed against the ESS criteria as part of a process to identify ecological conservation priorities for marine protected area network planning in the Northern Shelf Bioregion (NSB) (Gale et al. 2019). Information on each species was collated from species databases (e.g., the British Columbia Conservation Data Centre, General Status of Species in Canada), literature reviews, and species experts. The vulnerability, conservation status, and ecological role (upper-level predator, forage species, nutrient transporter, and habitat-forming species) of each species was evaluated and scored based on how well the species fit each criterion. Through this assessment, 65 fish and elasmobranch species, 46 invertebrates, and five habitat-forming marine plants and algae were identified as ecological conservation priorities. Of these species, 39 of the fish and elasmobranch species were identified as ESS: 26 scored high as upper-level predators, nine as key forage species, and seven as nutrient transporters. For the invertebrates, 33 were identified as ESS: four scored high as upper-level predators, 15 as forage species, and 17 as habitat-forming species. Four marine plants and algae were considered ESS because of their role in habitat formation.

Among the fish species identified as ESS, anadromous species such as Pacific salmon (including Chinook, Chum, Coho, Pink, Sockeye, Steelhead, Cutthroat Trout, and Dolly Varden) and Eulachon are considered ESS because of their contribution to nutrient transfer between ecosystems and their importance as forage species (Gale et al. 2019). In the adult phase of their life cycle, salmon are also important upper-level predators, as are other fishes that can be found in estuaries, such as Lingcod and Spiny Dogfish. Other estuarine species identified as ESS because of their role as forage fish include Pacific Sand Lance, Surf Smelt, Shiner Perch, and Pacific Herring. Several invertebrate ESS are also common in estuaries, such as Littleneck Clam and Bay Ghost Shrimp (Jeffery et al. 2023). While not identified as an ESS by Gale et al. (2019), Dungeness Crab were identified in an initial list of indicator species that can be used to help characterize estuarine ecosystems in support of marine spatial planning (MSP) in Washington State (Andrews et al. 2013), along with burrowing shrimp, oysters and clams, salmon, estuarine fishes such as Threespine Stickleback and English Sole, Green and White Sturgeon, and Sevengill Sharks. Further, eelgrass and macroalgae species (specifically Giant and Bull Kelp) were identified as ESS because of their role as biogenic habitats (DFO 2009b; Gale et al. 2019). These species were also identified as ecological conservation priorities for marine protected area (MPA) network planning in the NSB.

1.1.2.2. Sensitive fish habitat

Estuarine habitats such as eelgrass beds, kelp forests, and salt marshes are often provided as examples of sensitive fish habitats, but the term itself is not well defined. Habitat-forming species are among those that fall under the criteria for Ecologically Significant Species. In particular, eelgrass and macroalgae such as Bull Kelp and Giant Kelp have been identified as ESS in the Pacific Region (DFO 2009b; Gale et al. 2019). Additionally, DFO has developed a policy to help mitigate the potential impacts of fishing in sensitive benthic areas (DFO 2009c). Advice has since been provided to help identify significant benthic areas (SiBAs), which are defined as “ecologically and biologically significant habitat type, feature, community or species considered intrinsically sensitive to fishing impacts and slow to recover” (DFO 2019b). Those SiBAs that overlap with fishing pressures are considered sensitive benthic areas (SeBAs) (DFO 2019b). Guidance for fish and fish habitat protection also considers the sensitivity of habitats to non-fishing works or activities and recommends a risk-based approach based on the likelihood and severity of impacts (DFO 2019a).

For this project, significant fish and invertebrate species are defined as those that have been found to meet the criteria for Ecologically Significant Species (Gale et al. 2019). Sensitive fish habitats are defined broadly and similarly to SeBAs (DFO 2019b) as estuarine habitat types that are sensitive to, and with the potential to overlap with, a variety of detrimental fishing and non-fishing activities that were identified through a literature.

1.1.3. Estuaries as Ecologically and Biologically Significant Areas

In the Pacific Region, estuaries have been identified as Ecologically and Biologically Significant Areas (EBSAs) because of the diversity of habitats they contain and their importance for anadromous fishes, including Pacific salmon and Eulachon (Clarke and Jamieson 2006b; DFO 2013; Jamieson and Levesque 2014). EBSAs are areas of relatively higher ecological or biological significance that are important for healthy ocean services and require an elevated level of management or risk aversion (DFO 2004; Convention on Biological Diversity (CBD) 2008). Based on criteria developed for Canada by DFO (DFO 2004) and internationally by the Convention on Biological Diversity (CBD 2008), EBSAs can be identified for individual or multiple species or features, based on an area's uniqueness, importance for life history stages of species, importance for threatened, endangered, or declining species, vulnerability, productivity (aggregation), biodiversity, and naturalness (Rubidge et al. 2018). Within Canada, EBSA identification has typically happened at the scale of bioregions (Figure 1) and estuaries were first identified as EBSAs in the Northern Shelf Bioregion (NSB) through an expert-guided assessment (Clarke and Jamieson 2006a, b; DFO 2013). Experts noted that estuaries are important aggregation areas for anadromous fishes as they migrate upriver to spawn and also provide key habitat for feeding and growth, refuge from predation, and a transition zone between freshwater and marine environments for juvenile salmon—which have important fitness consequences. Subsequent EBSA processes in other Pacific regions, including the Strait of Georgia and Southern Shelf bioregions, confirmed river mouths and estuaries as EBSAs because of their importance for the aggregation, fitness, and productivity of anadromous fishes (Jamieson and Levesque 2014; Levesque and Jamieson 2015).

More recently, estuaries within the NSB were reassessed against the CBD EBSA criteria, as the initial assessment only included the DFO EBSA criteria (Rubidge et al. 2020). Estuaries were found to score high for the aggregation, special importance for life history stages, biological diversity, and productivity criteria. The scores for these criteria included rationales that extended beyond the importance of estuaries for anadromous fishes. The aggregation criterion was supported by its importance for adult salmon returning to spawn and evidence was provided for observed abundances of juvenile salmon, as well as Pacific Herring, Surf Smelt, and juvenile Dungeness Crabs in the Skeena River estuary (Carr-Harris et al. 2015; Moore et al. 2015). The role that estuaries play as important stopover sites for juvenile salmon (Moore et al. 2016) and migratory birds (Butler and Vermeer 1989; Ryder et al. 2007), contributed to the high score for special importance for life history stages, as did evidence that estuaries support higher growth for juvenile Dungeness Crabs (Gunderson et al. 1990; Rubidge et al. 2020). High scores for biological diversity and productivity were due to the elevated levels of nutrients found within estuaries that support a wide diversity of habitats as well as the large variety and abundances of species that use estuaries (Rubidge et al. 2020). Estuaries scored medium for the additional EBSA criteria of vulnerability, uniqueness, and importance for threatened species. Estuaries are considered vulnerable due to the widely documented degradation of many estuarine habitats, in particular salt marshes and eelgrass beds, and documented reductions in species abundance and diversity (Lotze et al. 2006; Borja et al. 2010). However, the dynamic nature of estuaries and variability of estuarine conditions due to natural physical disturbances has been suggested to contribute to their resilience against stressors (Rubidge et al. 2020).

While all estuarine bottlenecks across the BC coast should be considered as EBSAs (Clarke and Jamieson 2006b; Jamieson and Levesque 2014), a national workshop in 2007 suggested that designating specific estuaries as conservation priorities is an important step when gaps in the protection of nearshore and coastal ecosystems are identified (DFO 2007). Experts consulted in the Strait of Georgia and Southern Shelf bioregions identified the importance of large bottlenecks within Alberni Inlet and Barkley Sound for salmon and the Fraser River for salmon and Eulachon (Jamieson and Levesque 2014). Further, the Skeena, Nass, and Kitimat estuaries were noted as priority EBSAs in the NSB given their importance for waterbirds (Ryder et al. 2007). Given that EBSA identification and re-evaluation were both completed at a bioregional scale, no attempts were made to prioritize among estuaries, though a map of estuaries based on data developed by the Pacific Estuary Conservation Program (PECP; Ryder et al. 2007) was provided.

1.1.4. Pacific Estuary Conservation Program

Estuarine habitats such as eelgrass beds, salt marshes, and mudflats are also of great importance for a wide variety of marine birds. Estuaries provide essential stopover and foraging opportunities for migratory and resident species. The intertidal areas and associated delta of the Fraser estuary, for example, support as many as 1.7 million waterbirds and raptors annually, including 29 species at numbers considered significant at a global, continental, or national level (Butler et al. 2021). However, while these habitats of Fraser estuary are considered the most important migratory and wintering areas in Canada, they are also designated as “in danger” due to factors such as habitat loss and modification (Pacific Birds Habitat Joint Venture Technical Team 2022). The need to evaluate the importance of BC’s estuaries for waterbirds on a broader scale was identified by the PECP—a group comprised of representatives from government agencies (e.g., Environment and Climate Change Canada (Canadian Wildlife Service)) and non-profit organizations (e.g., Ducks Unlimited Canada and the Nature Trust of BC). Using orthophotos and spatial information on stream networks and coastal habitats, the PECP developed the most comprehensive spatial data for estuaries in BC, mapping 442 estuaries along the coast (Ryder et al. 2007). In addition to delineating estuary boundaries, the PECP also assessed relative importance of each estuary for waterbirds using a suite of metrics selected through conversations with species and habitat experts. The metrics were selected based on their comprehensiveness for the BC coast, data quality and scale relative to the mapped estuaries, and likely relationship with waterbird habitat (Ryder et al. 2007). These metrics included estuary size, habitat rarity, species rarity, herring spawn events, and waterbird density.

In 2019, estuary polygons were revised, removed, or added by the Pacific Birds Habitat Joint Venture (PBHJV) Technical Team (2020). The PBHJV is a partnership of government and non-governmental organizations established to conserve birds and their habitat along the Pacific coast of North America, including Hawaii and the Pacific islands. Due to the significant importance of estuaries for many species of migratory birds, they are a priority habitat type of the PBHJV, along with freshwater wetlands, agricultural lands, nearshore shallow marine waters, and riparian forests (Pacific Birds Habitat Joint Venture Technical Team 2022). In addition to the spatial updates to the estuary polygons, the PBHJV updated the estuary rankings for waterbird importance and removed habitat rarity because of the metric’s skewed distribution, while information on fall returns (escapements) of Pink, Chum, and Coho Salmon was added as a new metric (Pacific Birds Habitat Joint Venture Technical Team 2020). These rankings are used by the PBHJV to strategically conserve, restore, and steward ecologically important estuarine habitats. The data do not incorporate habitat condition or potential stressors and are considered applicable for work at a broad scale rather than site-specific assessments (Pacific Birds Habitat Joint Venture Technical Team 2020).

1.2. ASSESSMENTS OF ESTUARINE ACTIVITIES AND STRESSORS

Global research into estuarine species and habitat depletions has found exploitation and habitat degradation to be the primary historical drivers (Lotze et al. 2006) but expert-derived vulnerability assessments for estuarine habitats highlight stressors associated with climate change as exerting strong influences (Murray et al. 2024). Impacts to estuaries can originate in upstream environments, such as agricultural activities that contribute to increased nutrient loads in estuaries, or from marine and estuarine sources, such as habitat disturbance from development within estuaries or pollutants introduced by marine shipping activities. Marsh habitats in the floodplains surrounding estuaries have often been converted for agriculture or urbanization (Pacific Birds Habitat Joint Venture Technical Team 2022). As noted previously, estuaries are an important transition, foraging, and rearing area for juvenile Pacific salmon and impacts within estuaries may affect salmon populations (Sharpe et al. 2019). Research has shown that habitat degradation and loss within estuaries can reduce marine survival of Chinook Salmon (Magnusson and Hilborn 2003) and pollution within estuaries has also been linked to lower abundances of Chinook Salmon (Toft et al. 2018).

In the Rubidge et al. (2020) nearshore EBSA assessment, the EBSA criterion of naturalness was considered variable for estuaries in the Pacific Region because anthropogenic activities known to impact estuaries occur at varying levels across the BC coast and the analysis did not assess stressors associated with individual estuaries. The degradation of estuarine habitats has led to a variety of planning efforts at both local and regional scales along the BC coast. Estuary management plans have been developed for a selection of estuaries with a variety of spatial footprints, ecological and physical features, and potential impacts from marine and terrestrial activities. Focused research into different activities and stressors has been conducted in individual estuaries, and regional assessments have been completed to assess the overlap of estuaries with human activities.

For consistency, throughout this report we have followed the terminology for activities and stressors used in recent marine cumulative effects assessments and ecological risk assessment frameworks in the Pacific Region (Clarke Murray et al. 2015; O et al. 2015; Murray et al. 2020). Activities are defined as actions that may produce one or more stressors on the ecosystem under assessment (O et al. 2015). Hereafter referred to as activities, this includes anthropogenic activities such as commercial and recreational fisheries, as well as environmental impacts associated with climate change projections. Stressors are physical, chemical, or biological processes that, depending on the level of intensity, have the potential to change an ecosystem, habitat, or a component within (O et al. 2015). An activity can generate a stressor which can result in an impact to a species or habitat (Murray et al. 2020). The terms pressure or threat are sometimes used as a synonym for stressor. For example, policy guidance on fish and fish habitat protection in Canada identifies the potential for harmful impacts associated with the following threats (stressors): habitat degradation, habitat modification, aquatic invasive species, overexploitation of fish, pollution, and climate change (DFO 2019a).

1.2.1. Estuary Management Plans

In the 1970s, a series of technical reports were requested to summarize the available environmental information on a suite of 18 BC estuaries considered critical because of their ecological values and potential for development (Bell and Thompson 1977). Since that time, integrated planning for estuary management has also occurred on a site-specific basis, often initiated due to urban growth around the estuary or proposed developments with potential impacts to estuary habitats. For example, management planning began in the Cowichan-Koksilah estuary after increases in the demand for industrial use of estuarine area, such as log handling and storage operations (Lambertson 1987). Planning in the Campbell River estuary was instigated in response to proposed dredging activities (Penfold 2002). Proposed infilling for port development led to planning in the Squamish estuary (Squamish Estuary Coordinating Committee 1999). A total of seven estuary management plans have been developed along the BC coast, including the estuaries for Campbell River, Courtenay River, Cowichan River, Fraser River, Nanaimo River, Somass River, and Squamish River, while habitat classifications and assessments have been completed for several other locations. Common activities of concern noted in the plans include log handling, infilling of estuarine areas for industry or port development, water pollution from discharges, sewage disposal, agricultural runoff, and dredging (Williams and Langer 2002).

In 2002, DFO commissioned a review of estuary management case studies to help identify the best practices for development and implementation of estuary management plans (Williams and Langer 2002). The review focused on nine case studies and highlighted planning successes in two estuaries: the Campbell and Fraser rivers. Planning in the Campbell River estuary was considered unique in its focus on conservation and recreation, willing relocation of industrial activities, and broad stakeholder support. Work in the Fraser estuary by the Fraser River Estuary Management Program (FREMP) was considered the most comprehensive at that time. FREMP ran from 1982 until 2013 and included representation from federal and provincial agencies, port authorities, the regional district, municipalities, and First Nations. A key component of FREMP's effectiveness was the implementation of a coordinated project review process that was developed to streamline development requests, and associated environmental reviews for projects with the potential to harm aquatic and foreshore habitats (Williams and Langer 2002). In addition, FREMP created a shoreline classification approach to inventory estuarine habitats and provide greater clarity on the areas that could be considered for development. Shoreline segments were colour-coded red, yellow, and green based on habitat productivity and diversity and support for fish and wildlife with varying levels of restrictions and requirements for mitigation (FREMP 2003). Within the Fraser estuary, shorelines along the lower channels and marine deltas were coded red because they provide rearing and feeding habitat for juvenile salmon and staging habitats for migratory birds (FREMP 2003). This classification approach was adapted subsequently for many smaller estuaries (Williams and Langer 2002). However, a recent review of experts associated with FREMP also highlighted key gaps in the program's management effectiveness that should be resolved in future collaborative efforts, namely the lack of long-term funding, prioritization of industry and development, and the need for more effective co-governance and inclusion of Indigenous partners (Kehoe et al. 2021).

Key recommendations from the review of estuary management plans included following an ecosystem-based management approach and the need for cooperative planning and commitment from all relevant agencies and stakeholders (Williams and Langer 2002). As with FREMP, management planning for estuaries has typically included representatives from the federal and provincial agencies with jurisdiction for coastal and marine management. Planning has been done in partnership with regional districts, municipal governments, port authorities, and stakeholder groups. First Nations engagement varied among the planning processes reviewed by Williams and Langer (2002), but Indigenous governments are represented on the steering committees for more recent planning efforts, including the estuary management plans for the Nanaimo River (Catherine Berris Associates Inc. 2006) and Somass River (Catherine Berris Associates Inc. 2004) estuaries and updates to the planning for the Courtenay River estuary (Property Services Branch 2011).

1.2.2. Estuary-Specific Research Projects

The Fraser and Skeena are BC's largest estuaries with high biodiversity and ecological value for numerous species. Given their importance and high level of disturbance, many finer-scale research projects have been conducted on these estuaries, which can inform future management and conservation work at a finer-scale.

1.2.2.1. Fraser estuary

The Fraser estuary has been the site of multiple research projects on the impacts of anthropogenic activities that can provide further direction for estuary-specific management efforts. Upstream of the estuary, an approach for cumulative effects assessment has been developed that considers catchment area and flow accumulation to better evaluate threats to at-risk freshwater fish species (Boyd et al. 2022). Within the Fraser River watershed and estuary, Finn et al. (2021) used detailed information on stream barriers, historic vegetation records, and modeled stream networks to assess lost habitats for spawning and rearing juvenile salmon due to barriers to freshwater flow. Their results showed that large reductions in floodplains and linear stream segments have impeded connectivity for anadromous fish. As noted by Boyd et al. (2022), metrics associated with lost or disconnected stream segments may provide a more accurate assessment of freshwater diversions and associated stressors than metrics derived from limited barrier spatial data.

To inform future management planning, Kehoe et al. (2021) used a priority threat management approach to investigate potential management strategies for marine, freshwater, and terrestrial species at risk within the Fraser estuary. Using expert elicitation, species threats were identified and the probability of persistence for different species groups was calculated for potential management strategies that incorporated many of the activities used in this study. Restoration of aquatic habitats and ceasing major industrial development projects were found to be the most effective strategies, particularly for marine and anadromous species. However, pollution control and regulation of shipping and transportation were found to be cost-effective options that benefited many species. Co-governance by First Nations and other governments was found to increase the feasibility and effectiveness of all management strategies considered (Kehoe et al. 2021).

Additional work underway within the broader Salish Sea (which includes the Fraser estuary) is investigating early marine survival of juvenile Chinook, Coho and Steelhead Salmon in response to declining abundances (Pearsall et al. 2021). A committee of experts assessed potential impacts to marine survival of juvenile salmon and found the most critical impacts were predation, particularly by increasing populations of Harbour Seals, and factors affecting food supply, such as changing environmental conditions that influence zooplankton and forage fish. Among other projects, researchers are studying whether log booms may facilitate seal predation and thereby impact the survival of Chinook Salmon[1].

1.2.2.2. Skeena estuary

Within the Skeena River estuary, extensive work is being conducted on the health of habitats, particularly in relation to Pacific salmon. The Pacific Salmon Foundation has developed the Pacific Salmon Explorer[2], an online mapping tool that documents the status of conservation units for Pacific salmon. While much of the focus is on freshwater habitats, estuarine habitat

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[1] Pacific Salmon Foundation. 2022, Nov 25. Logs in B.C.'s Bays: Do Booms Influence Salmon Survival?

[2] Pacific Salmon Explorer

indicators, including eelgrass and macroalgae extents, sea surface temperature, dissolved oxygen, and the locations of relevant anthropogenic activities are documented for the Skeena River estuary. These indicators help monitor the state of salmon habitats and associated stressors or pressures. The indicators were identified using a conceptual model of pathways of effects for the Skeena River estuary that grouped the major pressures into categories based on water quality, habitat and food web impacts, and direct impacts to salmon populations (Pickard et al. 2015). Indicator development incorporated guidance, including pressure and state indicators, used to help monitor salmon conservation units under Canada's Wild Salmon Policy (WSP) (Stalberg et al. 2009). The development of indicators to support monitoring is also key to work by the Marine Plan Partnership (MaPP) in the area encompassing the Skeena estuary, with a focus on habitats such as canopy kelp, key species such as salmon, cultural values, and human wellbeing (Martone et al. 2018).

1.2.3. Regional Activity Assessments

The development of estuary management plans has required significant investments of time and resources for each location, and plans often take years or decades to complete (Williams and Langer 2002). Many of the activities and stressors of concern for estuaries are wide-ranging, with similar potential impacts across multiple estuaries. Similarly, many estuaries share comparable physical characteristics and suites of habitats and species. Broader scale planning efforts can improve the efficiency of estuarine conservation efforts that engage similar government agencies and stakeholders to address a similar suite of issues.

On the Pacific coast of the United States, a regional assessment of estuarine activities and stressors grouped estuaries based on the number and magnitude of stressors from marine, estuarine, and terrestrial sources (Merrifield et al. 2011). This work found that 59% of estuaries along the heavily populated coastline faced higher levels of activities and stressors and only 16% faced no or minimal stressors. A similar assessment for the Pacific coast of Canada built off the clustering methods of Merrifield et al. (2011) but results were different for the estuaries along the less developed coast of BC. In BC, 48% of estuaries were considered minimally threatened and 18% of estuaries, primarily those found near the urban areas of BC's south coast, were found to face higher levels of activities and stressors (Robb 2014).

The previously mentioned assessment of estuarine nursery habitats Pacific coast of the United States (Hughes et al. 2014) found through a review of relevant literature that habitat loss was the most common stressor for the study's focal species, though invasive species, hypoxia due to anthropogenic nutrient loading, pesticides from aquaculture, ocean warming, and sea level rise were also highlighted (Hughes et al. 2014). Three salmonids, Coho, Chinook, and Steelhead, were found to be associated with the most documented stressors or activities, though the authors acknowledge that may be due to the research effort associated with these ecologically, economically, and cultural important species.

More recently, Toft et al. (2018) assessed 20 estuaries along the Pacific coast of the United States to investigate the impact of multiple stressors on a suite of seven fish and invertebrate species that use estuarine habitats as nursery areas. Species included in the study were Chinook Salmon, Coho Salmon, Dungeness Crab, English Sole, Staghorn Sculpin, Shiner Perch, and Pacific Herring. Species abundances within the estuaries were compared to a national anthropogenic disturbance dataset that focused on land use in the estuary and watershed, alteration of stream flows, and pollution within the watershed. Chinook Salmon responded negatively to elevated pollution or flow changes, and English Sole responded negatively to increased land use (Toft et al. 2018).

1.3. REPORT OBJECTIVES AND STRUCTURE

The goal of this paper is to address the management need for a better understanding of the activities and stressors relevant to estuaries and the importance of individual estuaries to salmon, other significant fish species and the presence of sensitive fish habitat. Specifically, the objectives of the paper are to:

1. Review the current threats to estuaries in the Pacific Region.
2. Map the key ecological and anthropogenic features within Pacific Region estuaries, including:
   a. Anthropogenic activities and environmental impacts (including climate change); and
   b. Significant fish species and sensitive fish habitat.
3. Review and apply approach for estuary threat assessment, where data are available.
4. Identify estuaries of importance to salmon, other significant fish species (e.g., herring spawning areas), and presence of sensitive fish habitats (e.g., eelgrass), where data are available.
5. Examine and identify uncertainties in the data and methods.

In this document, we describe and apply a broad-scale approach for classifying estuaries across the Pacific Region based on the anthropogenic activities and environmental impacts that they may face. First, we describe a literature review that helped identify marine and terrestrial activities or stressors with the potential to impact estuaries. We then detail the development and compilation of spatial datasets to delineate these activities and stressors, which we then use in a cluster analysis to identify estuaries that share similar activity types and levels of use. The results of this analysis are compared to ecological metrics on the importance of estuaries for Ecologically Significant fish species and important estuarine habitats. Finally, we describe the results in context of other important work underway within the Pacific Region and outline how this work can focus future collaborative efforts at a finer scale. This work does not constitute a risk assessment and while activities and stressors are used to evaluate estuaries, the potential impacts on estuarine habitats and species are not assessed. Cumulative impact maps underway in the Pacific[3] are an important additional resource.

2. LINKING ANTHROPOGENIC ACTIVITIES AND ENVIRONMENTAL IMPACTS TO ESTUARIES

2.1. LITERATURE REVIEW

To guide the development of a list of anthropogenic activities and environmental impacts (hereafter referred to as activities) with the potential to impact estuaries in the Pacific Region, and their associated stressors, we performed a literature review using the Web of Science Core Collection. The search was completed using the following set of search terms (* represents a wild card, TS stands for “Topic”): ((TS=(estuar*)) AND TS=(*marsh* OR *eelgrass* OR seagrass* OR zostera* OR *flat* OR wetland* OR kelp* OR macroalga*)) AND TS=(threat* OR stressor* OR impact*) AND TS = (anthropogenic* OR human* OR climate*) AND TS=(British

[3] Agbayani, S., Schweitzer, C., and Murray, C.C. 2023. Cumulative impacts from anthropogenic activities and stressors on marine ecosystems in Pacific Canada. Ecosystem Stressors Program, Ocean Sciences Division, Fisheries and Oceans Canada, Sidney, BC.

Columbia* OR Washington* OR Oregon* OR Alaska* OR California*). The search was limited to articles and review articles published between 2010 and 2022 in English. Web of Science uses Keywords Plus in the Topic (TS) search, meaning that words or phrases that frequently appear in the titles of an article's reference list but do not appear in the article's title, author keywords or abstract are included in the query outputs. Because of this feature, several articles that described studies that did not occur in our geographic region of interest (Northeast Pacific Ocean) were included in our search output because of recurring geographic terms in the reference list that matched our search terms (e.g., Baja California) and were removed from further analyses.

We also searched the Government of Canada Publications database using the following set of search terms: estuary* AND (Pacific OR British Columbia). The search was limited to reports published in English between 2000 and 2022.

We reviewed each article for its relevance and identified the activities and environmental impacts referenced in the paper or that were the focus of estuary-based field studies. These activities and impacts were used to supplement and adapt lists of estuarine activities, environmental impacts, and associated stressors compiled for previous analyses in the Pacific Region (Robb 2014; Hodgson et al. 2020). Additionally, a recent report on the cumulative threats (stressors) affecting the Fraser Valley, a floodplain habitat in BC that is highly relevant (Boyd et al. 2022), was added to the final group of papers for review and used to add further activities and stressors to the flow diagram (see Figure 2 in Section 2.3 (Linking Activities to Stressors)).

2.2. ANTHROPOGENIC ACTIVITIES AND ENVIRONMENTAL IMPACTS

The literature searches for the Web of Science Core Collection and Government of Canada Publications search were done on April 28, 2022. The Web of Science search returned 109 results, of which 39 were removed from further analyses because they were not geographically or topographically relevant to our study (Appendix A, Appendix B included article references). The search of Government of Canada Publications database returned 14 results.

Below we summarize the various anthropogenic activities occurring within and in proximity to estuarine ecosystems and their associated stressors. Anthropogenic activities can be broadly divided into three source areas or zones: terrestrial, marine, and atmospheric. Anthropogenic activities, or climate changes stemming from anthropogenic influences, within these zones can generate stressors for estuary ecosystems. The following list of activities and stressors are the result of the literature review and previous review syntheses (e.g., Robb 2014; Hodgson et al. 2020) that are applicable to coastal estuaries in the Pacific Region. Although not all papers directly evaluated an anthropogenic activity's impact on estuarine health, we include where previous research has hypothesized or documented a link between an anthropogenic activity and estuarine ecosystem health. Note that these activities are not mutually exclusive, and their impacts can be multiplicative/synergistic and shared between many activity types and zones. Following the review provided below, Figure 2 illustrates the linkages between the zone of activity, the activities themselves, and the generated stressors on estuary systems.

2.2.1. Terrestrial Zone

Terrestrial activity can lead to pollution and sediment inputs into the estuary through nearby residential, industrial, agricultural and forestry activities (Watson and Byrne 2013; Robb 2014), and affect the ecology and habitat quality of these heavily impacted systems (e.g., Pacific salmon, Chalifour et al. 2019). Wetlands worldwide are threatened by urbanization of watersheds through infilling, fragmentation, and hydromodification (Fetscher et al. 2010). These activities can alter wetland physical structure, which decreases connectivity between habitat patches (Chalifour et al. 2019), hydrology, and biotic communities and leads to ecosystem-wide decreases in habitat quality (Fetscher et al. 2010; Robb 2014). Factors associated with the terrestrial zone include activities associated with human population size, urban areas and roads, agriculture, forestry (cutblocks and burning), freshwater diversions (dams), watershed pollution from mines, pulp mills, contamination closures, sewage and wastewater outflows, debris/litter, and shoreline development (Robb 2014). Below we describe some of the key terrestrial activities and their impacts on estuary ecosystems that resulted from the literature review. Additional literature on terrestrial activities and associated stressors that were not identified in the systematic literature review are highlighted in Section 5.4.1 (Literature Review Limitations and Uncertainties).

2.2.1.1. Development in watershed

Factors associated with development in the watershed include activities associated with human population size, urbanization, and roads. Coastal and non-coastal communities and human populations along the shorelines of estuaries and within upstream watersheds can impact estuaries and their biodiversity (e.g., bivalves, Novoa et al. 2016; eelgrass, Nahirnick et al. 2019). While the activities associated with human population and urban areas are numerous and overlapping, we separate out specific categories of anthropogenic development (e.g., agriculture and forestry) in the following subsections. The primary stressors arising from watershed development as they relate to human population and road infrastructure are pollution and sedimentation.

Pollution from human population growth and urban runoff is a contributor to non-point source pollution, and water quality declines within a watershed (Green et al. 2021). Urbanization and the high density of shoreline activity was associated with reduced water quality in BC eelgrass habitat via increased nutrient, sediment, and pollutant input (Nahirnick et al. 2019). Changes to the landscape (e.g., shoreline armouring, log booms, residential housing, docks) contributed to decreases in eelgrass area coverage and increased fragmentation of eelgrass meadows (Nahirnick et al. 2019).

In addition to pollution to estuarine systems, anthropogenic development and engineering can increase suspended sediment concentration, one of the most important contributors to turbidity, which influences habitat conditions and ecological functions of the system (Achete et al. 2015). Increases in sediment supply (due to hydraulic mining and deforestation) have been documented in various estuary systems (Watson and Byrne 2013), including the Sacramento-San Joaquin delta in California, which then also experienced a steep drop in sediment discharge (30% +) due to reservoir building and further estuarine clearing (Achete et al. 2015). Increased turbidity levels in estuarine environments limit photosynthesis activity by phytoplankton and microalgae, and in turn decrease primary production (Achete et al. 2015). Turbidity can also provide key habitat for endemic species. For example, in the San Francisco Bay-Delta estuary, the Delta Smelt seeks specific turbidity regions to hide from predators (cited in Achete et al. 2015: Baskerville-Bridges et al. 2004; Brown et al. 2013). Consequently, changes to turbidity levels through anthropogenic activity can have cascading effects on local ecologies (Achete et al. 2015).

Estuary habitat loss can also occur as the result of infilling or draining of wetland for development and/or agriculture (Gittman et al. 2019). While additional stressors associated with human population and road development could be hypothesized, results from the literature review were mixed. For example, neither watershed-level human population density nor measures of percent developed land surrounding sampled plant species in watersheds was significantly associated with relative percent cover of invasive species (Fetscher et al. 2010).

Although they found invasive species cover to be higher at southern California sites with anthropogenic modifications to tidal hydrology (e.g., tide gates, weirs). Percent of developed land uses within a perimeter of freshwater depressional wetlands have been found to be correlated with water quality and indicators of wetland condition (reviewed in Fetscher et al. 2010). Additionally, a study on a resilient eelgrass community in an urbanized estuary in Washington found no effect of upland development or human density on eelgrass presence or change through time (Shelton et al. 2017).

2.2.1.2. Agriculture in watershed

Agricultural activity within the watershed causes pollution (Alava et al. 2021), nutrient inputs, and sedimentation in estuarine systems, compromising water quality and contributing to habitat change. In California's San Francisco Bay estuary, urban development (primarily due to agricultural conversion) has contributed to the loss of over 90% of tidal wetland area (Parker and Boyer 2019). Urban development and agriculture alter salinity patterns by changing freshwater entering estuaries, leading to increases in nitrogen and salinity that in turn reduce the diversity of mixed species assemblages (Nelson and Zavaleta 2012; Ryan and Boyer 2012).

Agriculture can also be a source of pollution in estuaries (Green et al. 2021) through the use and flushing of herbicides, pesticides, fungicides, and veterinary pharmaceuticals into nearby waterways (reviewed in Boyd et al. 2022). These pollutants directly contribute to fish toxicity. In the Fraser River Valley, dichlorodiphenyltrichloroethane (DDT)-related compounds have been identified in flounder, and likely originated from atmospheric pathways and agricultural runoff from areas of the Fraser River Valley (Groulx et al. 2004). These agricultural pollutants create anoxic conditions, contribute to endocrine disruption in humans and wildlife, affect local food web ecologies, and contribute to habitat degradation (reviewed in Boyd et al. 2022).

Agricultural and rangeland areas are sources of high nutrient input to nearby water sources through runoff, erosion of overfertilized soils, and improper manure management for livestock and poultry (reviewed in Boyd et al. 2022). Nutrient inputs from agricultural activities in the watershed (e.g., nitrogen) may be contributing to macroalgal blooms and eutrophication (Moseman-Valtierra et al. 2010; Hood et al. 2016), which in turn threaten vascular wetland plants (Moseman-Valtierra et al. 2010), nursery habitat function and flatfish diversity (Hughes et al. 2015) through associated hypoxia and indirectly contribute to marsh erosion (Kennison and Fong 2014; Hood et al. 2016). Estuarine hypoxia has also been shown to negatively impact suitable fish habitat and the abundance of estuarine fish such as English Sole (Hughes et al. 2015). A study of macroalgae in Californian estuaries found that nitrogen concentrations did not directly influence abundance, and that physical modifications unique to each watershed (and their associated impact on salinity, organic content, sediment redox potential and other environmental variables) were the likely drivers of variation in abundance (Kennison and Fong 2014). Sedimentation from agriculture (and rangelands) occurs as the top vegetation layer is altered, exposing topsoil to drying, wind and runoff and increasing the amount of sediment entering local watersheds (Watson and Byrne 2013; Boyd et al. 2022), which can negatively impact habitat quality in estuaries.

The history and type of agriculture is also important to consider as it can lead to further changes in the estuaries through species invasions (e.g., Abbas et al. 2021). Coastal salt marshes are one of the mostly heavily invaded ecosystems globally (Grosholz 2002 cited in Abbas et al. 2021). An estuary with over 90% of its area converted to agricultural land through diking in the 1990s is now the site of a cordgrass (*Spartina densiflora*) invasion (Abbas et al. 2021). While it is not the agriculture itself that introduced the species, the history of modification has aided its success.

2.2.1.3. Forestry in watershed

Forestry activities have long played a role in the watersheds of BC. Forestry cutblocks, and the roads established to facilitate access to logging areas, modify and degrade habitats. The resulting stressors include pollution (Hodgson et al. 2020), sedimentation, and nutrient flushing. Like other built environments, forestry roads can be an upstream source of pollution. Pulp mills located along the shorelines of estuaries can result in habitat modification (Hodgson et al. 2020) and the discharge of pollution. Recently logged areas within the watershed can contribute increased sedimentation to marshland (Watson and Byrne 2013) and downstream rivers as the removal of vegetation exposes the topsoil (reviewed in Boyd et al. 2022). Similarly, vegetation removal and topsoil exposure contribute to nutrients being more easily flushed into freshwater systems, although the amount of nutrient input is dependent on harvest types (reviewed in Boyd et al. 2022).

Historical harvesting of forests may have contributed to reduction in the water quality of southern Gulf eelgrass meadows in BC via siltation (Nahirnick et al. 2019). Construction of a dryland log sort and log booming facility in the Campbell River estuary in BC resulted in the destruction of a large area of salt marsh (Anderson et al. 2000; Bravender and Anderson 2000). Furthermore, water quality of the estuary and Baynes Sound is affected mainly by logging, mining effluents, and sewage disposal (Jenkins et al. 2001).The Kitimat River estuary, located along the north coast of BC, is the site of historic (pulp and paper mill), current (aluminum smelter, commercial logging), and proposed industrial developments. Sampling at various sites in the estuary found significant differences in the infaunal community and abiotic sediment conditions between reference mudflats and mudflats potentially impacted by logging activities. The differences could not be linked directly to the logging activities at impacted sites; however, there were more observations of invasive species at disturbed sites (Gerwing et al. 2018).

2.2.1.4. Freshwater diversions

Freshwater diversions are created by anthropogenic structures that divert or obstruct the flow of water, and include dams, tide gates, and the extraction of river water (e.g., via a penstock). Physical modifications to estuary systems such as filling, diking, and channelization can alter the natural hydrology and water residence times of the ecosystem (Kennison and Fong 2014). Installation of hydrologic barriers, sediment restriction, and dredging all contribute to losses of wetland through conversion to unconsolidated shore and open water (Gittman et al. 2019). The resulting stressors of these diversions include flow change, habitation modification, entrainment, and a disruption of the connectivity of estuarine environments.

Dams are structures built across a waterway (river or stream) to hold back water and divert flow, and can result in fish entrainment. Dams can have large impacts on downstream habitats because sediment, habitat-forming large woody debris, and nutrients are sequestered behind the dams, altering sediment transport and contributing to erosion (reviewed in Foley et al. 2017). Furthermore, the movement of animals, particularly anadromous fish (e.g., Puntledge River, Hamilton et al. 2002; Elwha Dam, Foley et al. 2017), and their spawning and habitats are disrupted, changing migratory and gene flow patterns in resident fish populations. In river systems, dam removal is increasingly used to restore flow regimes (Hamilton et al. 2002), sedimentation, large woody debris transport, water properties (temperature and chemistry), and habitat connectivity (Foley et al. 2017). Dam removal on the Elwha River from 2011 to 2014 resulted in over a metre of sedimentation in the estuary and an expansion of the river mouth delta landform, which increased tidal habitat and reduced inputs of seawater into the estuary (Foley et al. 2017). As a consequence, the abundance of macroinvertebrates and fish in the estuary decreased and community composition shifted from brackish to freshwater-dominated species (Foley et al. 2017). In BC, salmon abundance decreased due to the expansion of the

Puntledge River dam. Mechanisms for the decline included difficulties passing over falls as a result of low flow levels, migration delay, injuries, and diversion of juveniles (Hamilton et al. 2002). To mitigate the effects of the dam, minimum flow requirements and powerhouse closures during adult salmon migration were implemented. Additionally, an artificial spawning channel was built to replace natural Chinook Salmon spawning areas and to provide a downstream route for emergent fry, however it did little to increase summer Chinook numbers and fry survival rates were low due to siltation (reviewed in Hamilton et al. 2002).

Hydrologic alteration occurs throughout southern California watersheds, and impermeable vegetation cover is correlated with increased peak flows and altered base flow (Howard et al. 2017). Modification of tidal hydrology from weirs or tidal gates was a highly significant predictor of relative percent cover of invasive plant species in third-order drainage basins in California estuaries, and systems with modified tidal regimes supported on average 8.5 times greater relative cover of invasive species than fully tidal systems (Fetscher et al. 2010). The San Francisco Bay-Delta estuary and its watershed is a highly altered and managed ecosystem. About fifty-five levied islands surrounded by deep and barren channels now replace marshlands, and a large fraction of the area is now managed wetlands. Large water pumping stations in the southern part of the Delta, and upstream regulation of the rivers have also dramatically altered the natural flow of water through the Bay-Delta estuary. These geomorphological and hydrological alterations have led to the loss of habitat connectivity through the separation and isolation of terrestrial and aquatic habitats, severe subsidence on the leveed islands, loss of habitat and biodiversity, and the deterioration of water quality (Fichot et al. 2016).

2.2.1.5. Burned areas in watershed

Burned areas in watersheds result in two stressors: sedimentation, and nutrient inputs. Wildfire activity burns off vegetation and exposes the top layer of soil to drying and erosion. Consequently, burned areas increase sedimentation in stream networks as the top layer of soil enters the water system (reviewed in Boyd et al. 2022). Similarly, the exposure of topsoil and surface hardening leads to a non-porous surface and increased nutrient flushing into stream networks (reviewed in Boyd et al. 2022).

2.2.1.6. Watershed pollution

Pollution of estuaries from terrestrial sources occurs through multiple industrial activities in the watershed (timber processing, mining, aluminum smelting, pipelines), and sewage and wastewater outflows. Industry activities stress local estuaries through pollution and sedimentation, and sewage and wastewater outflows are sources of inorganic and organic pollution and nutrient inputs. Pollutants entering estuaries from terrestrial development include mercury, ammonium, and microplastics. Additionally, pollutants from urban runoff and wastewater treatment systems contributes to nonpoint source pollution (caused by water moving over and through the ground and picking up pollutants), and the water quality of estuarine environments inevitably declines in response to human population growth within the watershed (Green et al. 2021).

Nonpoint sources of nutrients account for >50% of loads in coastal ecosystems, from agriculture, septic systems, urban runoff, groundwater, atmospheric depositions (Green et al. 2021). Historical physical modifications in watersheds have contributed to extremely high nutrient concentrations (NO_3, NH_4) in the water column and sediments of estuaries (Kennison and Fong 2014). Heady and co-authors (2015) found a strong correlation between estuary condition (e.g., hydrology, buffer habitat, plant diversity and structure, physical complexity) with nutrient levels (measured ammonia, nitrite, nitrate, phosphate). Such nutrient inputs have a negative impact on fish populations and are of particular concern in bar-built estuaries, which are used by juveniles of commercial species and as nurseries for imperiled species like steelhead. Furthermore, high nutrient inputs contribute to eutrophication (Heady et al. 2015; Hood et al. 2016) and decreased abundance and diversity of fish species (Heady et al. 2015).

Organic enrichment derived from human sewage (from municipal wastewater treatment), effluent (from pulp and paper mills, sawmills, wood treatment facilities), urban runoff, agricultural runoff, and aerial deposition (Groulx et al. 2004), can substantially alter infaunal communities and lead to anoxia and sulfide accumulation. This can further alter infaunal communities through toxicological effects and by increasing the rates of hypoxia (reviewed in Campbell et al. 2019). Shellfish harvesting areas have had to be closed due to high faecal contamination associated with sewage pollution within Comox Harbour and Henry Bay in BC (Jenkins et al. 2001). Contaminants from pulp and paper manufacturing and aluminum smelting have documented deleterious impacts on crabs, flatfish and clams (Gerwing et al. 2018).

Sediment contamination and associated negative impacts on infaunal communities occurs through pollution and industrial effluents containing polycyclic aromatic hydrocarbons, coppers, sulfides (Campbell et al. 2019). Anthropogenic sources of polycyclic aromatic hydrocarbons into the atmosphere of estuarine environments from terrestrial sources include coal, oil and wood combustion, transportation, aluminum smelters, steel and coking plants, municipal incinerators, agricultural, forest slash and open air burning and teepee burners at sawmills (Garrett and Shrimpton 2000). In the Fraser River system, dioxins, furans, chlorophenolics, and resin acids were found in higher concentrations at sites up to 300 km downstream of pulp and paper mills than in unaffected reference sites, though concentrations have decreased with abatement measures (Groulx et al. 2004). Fish and invertebrate species diversity changed and shifted to more pollutant-tolerant species in the estuary, furthermore juvenile Chinook were less abundant in areas of low dissolved oxygen while the Iona Island sewage plant discharged waste water onto Sturgeon Bank, as they were under more stress and susceptible to bird predation (Groulx et al. 2004). Within Baynes Sound, BC, the pH of the water is thought to be related to the sulfuric acid and sodium sulphate leeching from coal mines active in the 1900s (Jenkins et al. 2001). The level of vegetation in an estuary system also influences the degree of pollution. Experiments comparing the retention and movement of pathogen surrogates in mudflats and vegetated saltmarsh found that vegetated estuarine habitats are better able to filter zoonotic pathogens from the water compared to unvegetated (degraded) mud flats (Shapiro et al. 2010).

Mercury (Hg) contamination of estuaries can occur through global atmospheric transport even in areas that are far removed from sources, and Hg sources are often abundant near estuaries due to urbanization and industrial activities. Additionally, estuaries include habitats (tidal marshes and subtidal waters with low oxygen content) with hydrodynamics that favour retention of sediment particles and associated contaminants, contributing to methylmercury (MeHg) production and subsequent accumulation in the food web (reviewed in Davis et al. 2014). Hg and MeHg contamination, as a result of legacy mining, soil erosion, atmospheric deposition, and mineral spring discharge can threaten the health of wetland wildlife through increased exposure to the neurotoxin and biomagnification along trophic levels (McCord and Heim 2015). Further, fisheries are major vectors for human MeHg exposure (Davis et al. 2014). A study of Hg contamination in San Francisco Bay, showed that atmospheric deposition of Hg from coal power plants were not significant Hg sources and areas with known legacy mining showed the highest Hg levels of local watershed sites (Davis et al. 2014).

Further examples of contaminants, include ammonium, zinc and copper. Ammonium concentrations from wastewater effluents are one of many factors thought to contribute to the low productivity of the San Francisco Bay estuary (Fichot et al. 2016). Anti-fouling paint pollution resulted in elevated levels of zinc and copper in California waterways, with potential acute toxic effects on local fauna (Komoroske et al. 2012). Trace metal concentrations in sediment and bioaccumulation are a result of the different habitat characteristics and food web dynamics, however a study of San Diego Bay resident Green Turtles was not able to link specific metal contamination sources with toxic effects on the turtles (Komoroske et al. 2012).

Finally, coastal and estuarine environments often contain the highest levels of microplastics because of their proximity to human settlements. Further, wave and tidal action in estuaries facilitates the breakdown of macroplastics into smaller microfragments or microfibers (Alava et al. 2021). In the Cowichan-Koksilah estuary in BC, higher microplastic abundance in estuary water was detected on the north side of the estuary, which receives greater inputs from upland sources relative to the south side (Alava et al. 2021). A better understanding of exposure risk and the potential for bioaccumulation in wildlife species, including shellfish, Pacific Herring, Pacific salmon, and shorebirds that feed in estuaries and on the surface of intertidal mudflats is necessary in light of the widespread prevalence of microplastics in the marine environment (Alava et al. 2021).

2.2.1.7. Development of shoreline

Shoreline development through dikes, pulp mills, urban areas, mining, industry, hardened shorelines, pipelines, and roads stress estuarine systems via habitat modification, sedimentation, pollution, noise, and disrupted habitat connectivity. Shoreline debris, or the accumulation of litter, is also a source of pollution within estuary systems (Robb 2014).

Nearshore anthropogenic activity, such as shoreline alteration and development (e.g., armouring) negatively impacts estuaries and eelgrass beds via habitat loss (Rubidge et al. 2020) and increases impacts of sea-level rise and sediment availability (Watson and Byrne 2013). Noise pollution can stem from coastal development (Chalifour et al. 2019) and pile driving, which impacts resident fish populations (Hodgson et al. 2020). Residential and industrial developments can affect biofilm quality, abundance and distribution by altering the hydrology and sedimentation of the ecosystem, which in turn can negatively impact biofilm feeding species such as the Western Sandpiper (Jardine et al. 2015). In the Fraser River system, construction of shoreline infrastructure has led to sediment starvation and erosion, which, coupled with the impacts of dyke construction, infilling and irrigation further stresses estuarine systems (Groulx et al. 2004). In San Francisco Bay, California, a period of hydraulic mining for gold and damming in the watershed caused variations in fluvial sediment load and discharge into the estuary, resulting in considerable morphologic change in the estuary (Elmilady et al. 2019). Antibiotic-resistant bacteria in wetland sediments are often highest in urban centers and urban-impacted water systems, however natural wetland processes (sedimentation, predation) can decrease bacterial density (Kawecki et al. 2017).

In BC, the Skeena River estuary provides important nursery habitats for juvenile Pacific salmon. Coastal areas to the north of the estuary have been extensively developed, and include an international port, a papermill and several historic canneries. Surveys of the infaunal communities (invertebrates living in sediment) and environmental attributes of the estuary have shown that the communities are relatively undisturbed at the estuary scale, but have been affected by the history of industry at specific locations (e.g., the Cassiar Cannery) where passive reclamation did not return the communities to an entirely unstressed state (Campbell et al. 2020). Furthermore, shoreline developments are proposed for the future, including oil and natural gas pipelines, super-tanker routes, potash loading facilities, and a liquid natural gas terminal. More time may be necessary for the communities to return to an unstressed state, but a threshold of recovery may also exist beyond which the intertidal mudflats cannot be reclaimed through passive means (Campbell et al. 2019).

Shoreline armouring via human development of riprap breakwaters and seawalls, particularly in highly urbanized areas are used to prevent shoreline erosion and develop and protect shoreline property (Tronske et al. 2018). This form of shoreline development has been suggested to lead to changes in community structure, lower biodiversity, and the spread of invasive species (reviewed in Tronske et al. 2018). In combination with other shoreline and wetland development (dredging, channelization, infilling) these anthropogenic activities have contributed to large declines of naturally occurring wetland habitat, including drastic declines in Olympia Oyster (*Ostrea lurida*) (Tronske et al. 2018).

Estuary responses to shoreline development are not consistently negative. For example, in Southern Californian estuaries, there was no strong evidence that the percentage of developed land use in the surrounding drainage basin was a strong determinant of plant community composition (Fetscher et al. 2010). Additionally, a study on a resilient eelgrass community in an urbanized estuary in Washington found no effect of shoreline armouring on eelgrass presence or change through time (Shelton et al. 2017).

2.2.2. Marine Zone

Marine activity can affect the ecology and habitat quality of estuary systems via pollution, invasive species introductions, entrainment and habitat modification through shipping and boating, and fishery removals of biomass through fishing. Furthermore, estuaries can be exposed to activities and stressors occurring simultaneously within the marine and terrestrial zones which can have multiplicative/synergistic effects (Hodgson et al. 2020). Below we summarize some of the key marine-based activities resulting from the literature review and their impacts on estuary ecosystems. Additional literature on marine activities and associated stressors that were not identified in the systematic literature review are flagged below and in Section 5.4.1 (Literature Review Limitations and Uncertainties).

2.2.2.1. Development of estuary

A variety of marine activities and infrastructure can stress estuarine systems. For example, underwater submarine cables (Hodgson et al. 2020), floating homes/lodges, and log storage and handling (Groulx et al. 2004), lead to habitat modification, nonindigenous species introductions, magnetic field alteration, and pollution. However, more research is required to increase our understanding of any negative impacts of magnetic field alteration on juvenile salmon in estuaries (Hodgson et al. 2020).

Forestry activities extend into the marine environment in BC, with coastal areas used for log storage and handling. Commercial logging has impacted the Kitimat River Estuary via activities such as log sorting, storage, and booming, which has resulted in an accumulation of woody debris in the estuary and subsequent organic enrichment of intertidal sediments (reviewed in Gerwing et al. 2018). Log handling, sorting, and dumping has also been suggested as significantly impacting the vegetation, substrate, and shape of the Courtenay River estuary basin in BC, which has also been subjected to dredging for marina and wharf construction, and sewage disposal (Jenkins et al. 2001). Furthermore, the mudflat surrounding Cassiar Cannery near the mouth of the Skeena River, an estuary in BC, experiences physical disturbance to the sediment from logs that are transported down the Skeena River and ultimately accumulate on the mudflat, potentially resulting in organic enrichment (Campbell et al. 2019). Abandoned piles and sawdust and extensive logging could be sources of resin acids to rivers (Groulx et al. 2004).

Habitat modification resulting from estuary development can lead to habitat fragmentation and disruption of connected of estuarine seascapes. This can be detrimental to estuarine function as connected seascapes of different habitat types maintain greater biodiversity and productivity in estuary systems (Chalifour et al. 2019). Research in the Fraser estuary on Pacific salmon species showed that focusing habitat remediation efforts solely on eelgrass could lead to further declines in salmon populations with the loss of remaining marsh (Chalifour et al. 2019).

Additionally, coal port and ferry terminal causeways in the Fraser estuary block the flow of river water, resulting in the expansion of nearby eelgrass meadows due to the clearer, more saline water in the estuary. The causeways have also significantly lengthened the distance that emigrating salmon must travel between the river mouth and the densest eelgrass habitat (Chalifour et al. 2019). Restoring tidal inundation in this area would increase habitat connectivity and marsh habitat use by young salmon, and potentially mitigate the severe reduction and recession of brackish marsh due to anthropogenic development in the estuary (described in Chalifour et al. 2019). Additional references relevant to log handling and storage operations and coastal infrastructure that were not identified in the literature review are noted in Section 5.4.1 (Literature Review Limitations and Uncertainties).

2.2.2.2. Shipping and boating

Estuaries are susceptible to multiple stressors resulting from shipping and boating activities. These stressors include anchorages, ports and terminals, docks, marinas, derelict vessels, dredging, vessel traffic and recreational boating. Marinas, anchorages (commercial and recreational) and port facilities are all sources of pollution and can lead to habitat modification (Rubidge et al. 2020). Development and installation of these facilities and the associated commercial and recreational vessel traffic can also produce pollution (Garrett and Shrimpton 2000; Hodgson et al. 2020), introduce invasive species, and modify benthic and shoreline habitats, further impacting the habitats and biodiversity of estuaries. Dredging is also done within estuaries to ensure safe passage for ships, which can modify benthic environments at the dredge and disposal sites and lead to pollution, entrainment and habitat modification. Vessel traffic produces boat wake (Robb 2014), and the additional water movement can contribute to marsh erosion (Hood et al. 2016).

In terms of biogenic habitat, vessel activity impacts seagrass beds in variety of ways. Motoring and anchoring in seagrass beds uproots and scours the vegetation and vessel discharge is a source of contamination to eelgrass meadows (Rubidge et al. 2020). In San Francisco Bay, boats damaged up to 41% of eelgrass beds through illegal anchoring (Kelly et al. 2019), and in the Southern Gulf Islands, BC, increased recreational boat traffic and dock installations were correlated with increased fragmentation and reduced habitat coverage of eelgrass meadows (Nahirnick et al. 2019).

The construction of ports can lead to extensive habitat loss and modification (Groulx et al. 2004). For example, when the railroad line was extended into the Cowichan-Koksilah estuary to provide access to a deep-water seaport in the 1920s, over 40 acres of prime saltmarsh and intertidal area was infilled (Alava et al. 2021). Additionally, dock construction could have influences on local fish health. In central Oregon, Black Rockfish growth was found to be higher in eelgrass versus dock habitat in years when upwelling was reduced. However no difference in growth was recorded in a year with increased upwelling, suggesting that in years when ocean conditions are variable, the dock structure provides lower quality and less consistent habitat compared to eelgrass (Schwartzkopf et al. 2021).

Dredging, the removal of material from a waterway, is often done to aid vessel navigation and maintain sufficient depths for commercial fishing (Walter et al. 2018). The resulting deep channels may stress marsh systems by increasing tidal currents, marsh erosion and by creating sediment sinks (Groulx et al. 2004) that compete with the marshes for sediment (Hood et al. 2016). Consequently, dredging is a source of habitat modification (physical removal of material) and sedimentation changes and has caused extensive damage to eelgrass meadows (Rubidge et al. 2020). Globally, dredging has been estimated to account for the loss of over 21 thousand hectares of seagrasses due to direct removal and indirect habitat modification (Walter et al.

2018). Dredging was also reviewed by Hodgson and coauthors (2020) as being linked to pollution, albeit with low confidence.

The types of pollution associated with shipping are not often detailed within the papers of this review; however, in addition to oil/petroleum inputs (Garrett and Shrimpton 2000), pollution could also include noise, and other organic and inorganic contaminants (see Literature Review Limitations and Uncertainties). Additionally, invasive species are also introduced to estuary systems through shipping and boating (see Section 2.2.2.6 below).

2.2.2.3. Aquaculture

Shellfish and finfish aquaculture operations within estuaries have the potential to modify benthic habitats and the shoreline areas used for infrastructure. Specifically, environmental degradation of wetlands from aquaculture operations can occur through land conversion, waste discharge, saline intrusion, water quality, and water availability (Ottinger et al. 2016). In estuarine environments, aquaculture operations can disturb benthic organisms, cause shading that can negatively impact marine vegetation, and cause increases in nutrients, chemicals, and detritus. Finfish aquaculture also has the potential to introduce aquatic invasive species. Stressors generated by aquaculture activities include pollution, sea lice, bacteria, and invasive species introductions (Hodgson et al. 2020).

Within the literature review, shellfish aquaculture sites were found to be a vector for introducing invasive benthic species to eelgrass beds, and over 50% of invasive species in eelgrass habitats have known negative impacts to eelgrass health (Mach et al. 2017). Furthermore, a long-line and on-bottom oyster aquaculture expansion project in Washington was shown to slightly reduce eelgrass density (Muething et al. 2020). The Hodgson and coauthor (2020) review of impacts of anthropogenic activities on juvenile salmon found several studies that documented increased sea lice numbers on salmon closer to salmon farms, causing damage to salmon health (Hodgson et al. 2020). Research on aquaculture outside of those resources identified in this literature review have suggested varying relationships between aquaculture and pathogenic load in the environment (see Literature Review Limitations and Uncertainties).

2.2.2.4. Marine pollution

Estuaries are ecosystems with direct ties to both terrestrial and marine ecosystems and are exposed to activities and stressors coming from multiple sources. Pollution originating in both terrestrial and marine zones may impact estuarine biodiversity and ecology (Hodgson et al. 2020; Alava et al. 2021). In contrast to Section 2.2.1.6 (Watershed pollution) where pollution sourced from terrestrial activities is discussed, here we detail pollution that originates in the marine zone. Marine pollution through petroleum discharge/spills (accidental discharges) and operational discharges by vessels is a source of pollution for estuary systems. While the studies in this literature review did not deal with marine sources of pollution directly, previous research into oil spills, vessel traffic contamination, and the acknowledgement that upstream sources of pollution exist for estuarine systems (Hodgson et al. 2020) still deserves mention. Furthermore, proposed changes to super tanker routes in areas near the Skeena River estuary (Campbell et al. 2020) pose potential future stressors in the form of marine pollution to estuarine systems.

Spillage of petroleum products, coal and creosote introduce polycyclic aromatic hydrocarbons (PAHs) to the marine environment. Oil spills from vessels and leakage from marine oil drilling can contribute petroleum-base PAHs to marine waters (Garrett and Shrimpton 2000). In the Fraser estuary PAHs have been detected in mussels, clams, and English Sole, and PAH concentrations in fish exceeded those found in fish from reference areas (Garrett and Shrimpton 2000).

In addition to petroleum-based pollution, microplastics enter estuaries through marine activities such as fishing and shipping. The marine shipping terminal in the Cowichan-Koksilah estuary, BC, is likely one source of microplastics in the estuary, in addition terrestrial sources such as household wastewater (Alava et al. 2021).

2.2.2.5. Resource extraction

Commercial and recreational fishing occurs within estuary environments, extracting marine resources and stressing estuaries through fishery removals of aquatic biomass and habitat modification. Fishing activities remove fish biomass from estuaries, including both target and non-target (bycatch) species (Robb 2014). In addition to removing biomass, commercial fishing can reduce species diversity and impact demersal fish communities through habitat loss, degradation and pollution (Reum and Essington 2011). Depending on the gear used and its contact with the seafloor, commercial and recreational fishing activities also have the potential to modify and disturb benthic habitats (DFO 2009c). In four California estuaries, over-harvesting and destructive fishing practices contributed to declines in large bivalve species (Novoa et al. 2016). While the stressors for resource extraction are limited to fishery removals and habitat modification in the literature examined here, it is important to note that depending on the size of the vessel used to extract marine resources, noise pollution may also occur. Noise pollution is discussed broadly as pollution in Section 2.2.2.2 (Shipping and boating). Also, while the stressors provided here are proximal to the activity itself, we acknowledge that indirect stressors may also originate from these activities. For example, species removals may impact community composition by facilitating competitive advantages and invasions by estuarine species. Additional relevant references that were not identified in the literature review are noted in Section 5.4.1 (Literature Review Limitations and Uncertainties).

Habitat modification and loss can also occur when the water within an estuary is extracted for irrigation use in nearby agricultural or urban areas (e.g., Fraser River Delta, Groulx et al. 2004). Finally, oil extraction within the marine (and terrestrial) environment can also occur, resulting in habitat degradation and loss (Gittman et al. 2019) as well as pollution for proximal estuary systems.

2.2.2.6. Invasive species

Invasive, or non-native species with deleterious effects, impact marine and estuarine systems through alterations in community structure and the physical habitat (Mach et al. 2014; Mach et al. 2017; Hodgson et al. 2020). Invasive species can be directly introduced into an estuarine system through international shipping to ports, ballast water, hull fouling, improper cleaning of boats between waterways, and aquatic species migrations. Trans-Pacific shipping has resulted in the introductions of several marine species (particularly seaweeds and invertebrates) to the coastal and estuarine ecosystems of the Northeast Pacific (Mach et al. 2014). In BC, the majority of invasive species introductions have been hypothesized to have arrived via shipping ballast and hull fouling, in addition to the import of aquaculture species (detailed above; Mach et al. 2017). Here we are describing invasive species introduction through marine inputs, although terrestrial disturbance and land modification could provide a competitive advantage to species invasions within estuary systems. Aquatic invasive species generate three stressors: invasive introduction, competition, and habitat modification.

Introduced species triggered fluctuations in estuarine bivalve diversity and community structure over a 30–50 year time span in Californian estuaries. Community turnover was attributed to lower bivalve species richness, loss of large or deeper-dwelling native species and invasions of small surface dwelling species (Novoa et al. 2016). In addition, comparisons of modern foraminifera communities with sediment fossils in the South San Francisco Bay estuary showed that the modern community has been decimated by the introduced species *Trochammina hadai*, from Japan. The mechanism by which *T. hadai* was introduced is not mentioned, however the species dominated the modern foraminifera communities within 10 years of invading (Lesen and Lipps 2011). In Boundary Bay, BC, at least three species present in benthic samples (the polychaete *Polydora ligni*, the gastropod *Batillaria zonalis*, the bivalve *Mya arenaria*) are related to the introduction and maintenance of Atlantic (*Crassostrea virginica*) and Pacific (*C. gigas*) Oysters for commercial production in the 20th Century (Sewell and Elner 2001). The initial introduction of these oyster species and the inadvertent introduction of six bivalve species, seven gastropod species, four polychaetes and other invertebrates in Boundary Bay and other locations may have influenced current species prevalence and abundance within the sandflats (Sewell and Elner 2001).

Zostera japonica, an eelgrass species, arrived in two estuaries in Washington early in the 20th century, and is one of four eelgrass species to have been transported outside their native ranges. Introduction is thought to have occurred with the transfer of propagules during the oyster trade in Japan, and while *Z. japonica* has not been shown to impact native seagrass species in the Northeast Pacific, it modifies unvegetated mud- and sandflat environments (Mach et al. 2014). A metanalysis suggests that *Z. japonica* increases overall diversity of infaunal invertebrates, but decreases large infaunal species (Manilla Clam, Ghost Shrimp) compared to unvegetated mud flats (Mach et al. 2014). Chinook Salmon were not found in the reviewed research to slow their swimming speed in *Z. japonica* dominated eelgrass beds as they do in *Z. marina* (native species) dominated systems, suggesting they are not using non-native eelgrass as protective habitat. Furthermore, when *Z. japonica* and *Z. marina* compete for space, in most instances both species experience reduction in shoot density and biomass (Mach et al. 2014).

In a study of introduced macroinvertebrate and algal species in eelgrass beds in BC and their relationship to shipping and aquaculture vectors and environmental factors, Mach and coauthors (2017) found that shipping activity was not strongly correlated with the richness and abundance of nonnative species. This contrasts with previous work that found shipping to be an important vector in the introduction of molluscs, arthropods, and annelids to seagrass beds in the Northeast Pacific (Williams 2007 referenced in Mach 2017). This discrepancy is hypothesized to be the result of recent regulations that require mid-ocean exchange of ballast water, which reduces species introductions, as well as a potential limitation in the sampling method used (Mach et al. 2017).

Associated with wetland and shoreline development and the modification of wetlands, bays, and estuaries is a rise in non-native species introductions. In southern California, very high proportions of non-native species exist on human-made habitats including floats and subtidal fixed structures, with potential negative impacts on native species populations (Tronske et al. 2018). Species have also been intentionally introduced into estuarine systems, such as the Pacific Oyster (*Crassostrea gigas*) which was planted in California in the 1920s, and is now found along the coast (Tronske et al. 2018). Striped Bass, a non-native anadromous fish, that was introduced to California in 1879 to support a commercial fishery, is an extreme piscivorous predator at larger size-classes in the San Francisco Bay-Delta ecosystem. It has the ability to exploit migration bottlenecks, which has potential for large impacts on emigrating salmonids in the estuaries and rivers of the California coast (Boughton 2020). Even decades after their initial introductions, marine species introductions are modifying and influencing estuarine systems and their ecologies.

2.2.3. Atmospheric Zone

Climate change, resulting from increased concentrations of greenhouse gases within the atmospheric zone is currently affecting, and is projected to affect, estuary ecosystems. Warming global temperatures increase the air temperature and the water temperature of both marine and freshwater systems and because estuaries exist at the marine-terrestrial interface, they are subject to both tidal inundation and exposure to air and are thus highly susceptible to significant and irreversible damage from climate change impacts. Increasing temperatures, rising sea levels, and acidification are causing higher, more extensive and more frequent inundation events and modifying the patterns of salinity of estuaries and salt marshes and their associated low-lying habitats. Wetland plant communities may already be stressed by anthropogenic disturbance, so the additional impacts of El Niño or sea level rise (SLR) may exacerbate existing stressors by affecting inundation, salinity, or freshwater inputs into wetlands (Goodman et al. 2018). Wetland responses to such variations include changes in surface elevation, distribution of the wetland-terrestrial interface, spatial extent, and sediment composition. Furthermore, toxic cyanobacterial blooms have been attributed to a wide variety of environmental factors including nutrient pollution, increased temperature, salinity, water residence time, vertical stratification, and pH, many of which will likely be exacerbated by climate change (Howard et al. 2017). The individual and combined stressors associated with climate change could affect biotic processes, biodiversity, primary and secondary productivity, nutrient cycling, and lead to an increased prevalence of invasive species and disease vectors, and a predominance of short-lived opportunistic species (reviewed in Morzaria-Luna et al. 2014).

2.2.3.1. Sea level rise

Actual and projected SLR threaten intertidal areas and associated estuarine ecosystems worldwide (Elmilady et al. 2019) and leads to habitat modification within estuary systems. The current global SLR rate is the highest it's been in the past two centuries and is projected to further increase from 0.2 m to ~ 2.0 m by the year 2100 (Elmilady et al. 2019). The current accelerated trends in SLR are expected to shape the future states of estuarine systems in several ways, including through intensifying salinity and permanent submersion in salt marshes (Thorne et al. 2012; Gallego-Tévar et al. 2020); shoreline erosion (Thorne et al. 2012); loss of salt marshes, and coastal wetlands (Thorne et al. 2018; Elmilady et al. 2019); increased inundation and flooding (Thorne et al. 2012); the decline of intertidal area (Elmilady et al. 2019); and the conversion of palustrine (non-tidal) wetlands to estuarine wetlands, unconsolidated shore, or open water (Gittman et al. 2019). Impacts associated with sea level rise may be more extreme in estuaries where the built environment (e.g., dikes, levees, and human coastal land use) restricts inward migration of estuary habitats (Grewell et al. 2013; Zhang and Gorelick 2014). Local rates of sea level rise, local topography, and wetland morphology will all shape how individual estuaries are impacted by SLR and each estuary's feedback loop between inundation, plant growth, organic matter accretion, and sediment deposition (Doughty et al. 2019).

Even under a low SLR (0.3–0.5 m) scenario, global assessments report wetland losses up to 22%–59% and up to 78% with for high SLR scenarios (1.1 m; Doughty et al. 2019). Recent modeling work by Doughty et al. (2019) suggests that that when coastal wetlands (vegetated marsh and unvegetated flats) are not able to migrate inland, the southern California region could experience combined wetland habitat losses of 12% (0.6 m SLR) and 48% (1.7 m SLR). These losses increase to 25% and 68%, respectively, when only vegetated marsh is considered. A recent modeling study for a sub-embayment of the San Francisco Bay showed that SLR slowly drowns the intertidal environment, and that the rate of SLR is higher than the accretion rate of the mudflats (Elmilady et al. 2019). Further, the impacts of SLR are strongly linked to suspended sediment concentrations and will variably impact the San Francisco Bay (Parker and Boyer 2019). Modelling studies showed that saltmarsh habitat in intermittently closed estuaries (ICE) is more resilient to sea level rise because closure events allow for higher accretion rates (when coupled with sediment delivery events (e.g., fluvial pulses)) compared to open estuaries in California (Thorne et al. 2021). In addition to habitat loss and modification, SLR can also threaten the ability of salt marshes to trap and filter nitrogen, which buffers coastal areas from eutrophication (Nelson and Zavaleta 2012).

Vertical accretion in salt marshes driven by sediment deposition and organic matter may alleviate the impacts of SLR (Gallego-Tévar et al. 2020), however, salinity and inundation depth are increasing in salt marshes. Consequently, it is predicted that sediment accretion will not compensate for SLR (Thorne et al. 2018; Rosencranz et al. 2019), and abiotic stress will intensify for wetland vegetation (e.g., halophytes) and contribute to submergence of intertidal habitats by the end of the century (Thorne et al. 2018; Gallego-Tévar et al. 2020). Under accretion limitations, 63% of salt marsh will not be able to increase in elevation quickly enough to keep pace with climate change in California (Thorne et al. 2014). Furthermore, marsh drainage is affected by SLR, with lower saltmarsh biomass observed in poorly drained areas (Schile et al. 2011). The potential near-future SLR in the Pacific northwest could also increase volumes of displaced littoral (beach) sand in large estuaries and contribute to beach erosion (Peterson et al. 2021).

Species responses to changes in SLR are expected to be variable and depend upon a variety of factors, including the degree of SLR, species tolerances to altered habitat and ecological linkages. Many species may lose a significant portion of their current range and face extinction or local extirpation when SLR results in a loss of habitat or habitat connectivity, limiting the ability for species to migrate or disperse—a scenario that is projected for two rare estuarine plant species in San Francisco Bay (Grewell et al. 2013). In contrast, low and moderate SLR scenarios and associated increases in salinity have a positive effect on Clapper Rail (a marsh bird) populations in California by promoting higher quality nesting habitat and an abundance of macroinvertebrate prey (Zhang and Gorelick 2014). However, moderate and high SLR leads to saltmarsh habitat loss (Zhang and Gorelick 2014). SLR can also threaten wetland wildlife, such as the endangered Salt Marsh Harvest Mouse (*Riethrodontomys raviventris*), by causing flooding, habitat fragmentation and loss of *Salicornia pacifica* habitat in San Francisco Bay (Marcot et al. 2020). For vegetation, the overall productivity of brackish marsh plants in California is sensitive to increased flooding and salinity changes with SLR, although specific species responses vary (Janousek et al. 2020). Phenotypic plasticity in leaf functional traits was also observed in experimental populations of invasive cordgrass species (*Spartina densiflora*), allowing them to maintain invasive growth in response to rising estuarine salinity (Grewell et al. 2016). Furthermore, sea-level lowering in Alaska (due to postglacial land rebound) may impact eelgrass habitats and estuarine species as a result of land emergence and greater land exposure along the shoreline (Johnson et al. 2019). Eelgrass located in more protected shorelines and in small estuaries with shallower slopes was predicted to be most vulnerable (Johnson et al. 2019). Additionally, laboratory and field experiments suggest that variations in SLR impacts eelgrass by reducing irradiance reaching eelgrass communities during El Niño events (Thom et al. 2014). SLR also opens up potential for expansion of a range of invasive plants to estuaries with changing salinity levels (Gallego-Tévar et al. 2020; Gillard et al. 2021).

2.2.3.2. Precipitation change

Estuarine systems are projected to experience more frequent and unpredictable high-volume precipitation events (Thorne et al. 2012; reviewed in McAlpine-Bellis et al. 2021). Changes in future precipitation due to climate warming will result in flow change within estuarine systems. Managed estuaries (e.g., estuaries influenced by dams and levees) are expected to experience an increase in flooding events, storm surge stress on infrastructure (Morzaria-Luna et al. 2014; McAlpine-Bellis et al. 2021), and increased precipitation. Changes in the predictability of precipitation events will alter the seasonality of salinity (Thorne et al. 2012; McAlpine-Bellis et al. 2021) and the composition of associated vegetation communities (Thorne et al. 2012); impact salmon in the early/late stages of their life cycle (Groulx et al. 2004); cause erosion (Groulx et al. 2004; Thorne et al. 2012); high turbidity (Groulx et al. 2004); plant drowning; decreased shoreline stability; and increased susceptibility to scouring (Casazza et al. 2021). Tidal wetland vegetation may also respond to changes in precipitation, which in turn affects soil saturation, pore water salinity, and freshwater discharge rates into estuaries. Where soils are normally hypersaline, such as in Southern California marshes, increased rainfall could reduce salinity levels, resulting in increased plant growth and greater seed germination (Goodman et al. 2018), as less above ground plant productivity exists at higher salinities in poorly drained sites (Schile et al. 2011).

Interannual variation in inundation or precipitation due to El Niño and the Southern Oscillation (ENSO) could amplify the impacts of anthropogenic stressors through tipping points and their resulting alternative stable states, increasing the impact of other stressors to the long-term sustainability of tidal wetland ecosystem services (Goodman et al. 2018). Increased estuarine flooding during El Niño events has the potential to impact a variety of non-tidal wetland resources, including infrastructure (dams, seawalls, roads, pipes or water treatment plants). Tidal wetlands act as a natural barrier to flooding and absorb excess water in urban landscapes, however most tidal wetlands on the Pacific coast have been degraded, hardened and/or disconnected, decreasing their ability to mitigate flood action (Goodman et al. 2018). Interestingly, enhanced El Niño conditions may improve oxygen conditions in hypoxic areas through increased flushing and suppression of upwelling, and overall enhance estuaries that suffer hypoxia (Hughes et al. 2015). Severe flooding and destructive storm swells may be compounded during El Niño winters with higher wave energy and seasonally elevated water levels, posing increasing stressors to coastal habitats (Goodman et al. 2018). Furthermore, future climate warming could change the source of winter precipitation from snow to rain (e.g., Skagit basin, Hood et al. 2016) increasing winter river discharge, winter peak flows and associated sediment transport. By contrast summer flows and sediment transport will be decreased. The resulting asynchrony between sedimentation in the marsh and vegetation growth will decrease sediment retention in delta marshes (Hood et al. 2016). Furthermore, the floodwaters can result in higher nitrogen and sediment loading within wetlands and alter the nitrogen sources for vascular plants resulting in altered trophic pathways within wetlands (Moseman-Valtierra et al. 2010). A laboratory study of eelgrass species in California found that despite the infrequency of cold extremes and freshwater flushes within Californian estuaries, the imposed stress may shape eelgrass ecosystem dynamics by impacting the survival of key species (McAlpine-Bellis et al. 2021).

In contrast to flooding events, extreme drought events can also occur due to climate change and changing precipitation levels, which can persist across multiple years (IPCC 2018). Severe droughts and associated salinity stress has caused large-scale diebacks of native foundation species in salt marsh ecosystems (Wigginton et al. 2020). The impact of salinity on salt marsh plant communities depends on the duration of the salinity change. For example, short term events can lead to biomass changes but not compositional changes, whereas long term changes can lead to a replacement of species, such as halophytes being replaced by freshwater wetland plants (Wigginton et al. 2020). In a study of vegetative changes in California, Wigginton and coauthors (2020) proposed that extreme droughts favored native plant success over invader success in estuarine tidal marshes as invasive plant species experienced diebacks due to salinity stress. The native species were predominantly halophytes and adapted to acute salinity changes.

2.2.3.3. Global temperature

Increasing global temperatures will impact estuaries through both the terrestrial and aquatic interface. Future increases in global temperatures can modify freshwater flow into estuaries, with decreases in the summer and increases in the winter, due to declines in the duration of mountain snowpack (Parker and Boyer 2019), changes to precipitation and increasing storm surges (Robb 2014). Additional impacts of warming temperatures are also expected as species are pushed to their thermal tolerances and local ecologies are disrupted. For example, increasing global temperatures and melting glaciers in Alaska has led to increased freshwater discharge into coastal regions, causing reductions in salinity and light attenuation due to higher turbidity and sedimentation rates. Experiments with kelp growth from these impacted areas found that overall growth rates decreased with decreasing salinity and irradiance. However, some degree of phenotypic plasticity was observed that may mitigate the impacts of habitat change (Spurkland and Iken 2011).

2.2.3.4. Water temperature

We differentiate stream and sea surface temperature from global temperature (air temperature) as flowing and sea surface water will experience different temperature changes than the global atmosphere depending on location, currents and water depth, among other factors. The generated stressor for an estuary system is the change in water temperature itself, and its effect on local ecologies.

The few studies in the literature review that mentioned changing water temperature predominantly focused on sea surface temperature changes. Ocean warming can prevent nutrient exchange in coastal wetlands and trigger physiological responses (metabolic rates, behaviour, etc.) that may threaten species survivorship and productivity (Morzaria-Luna et al. 2014). Increases in sea temperature can also affect plant productivity in wetlands (Parker and Boyer 2019). The success for the establishment of invasive species in eelgrass habitats is attributed to changes in sea surface temperature and salinity (Mach et al. 2017), and laboratory experiments showed that eelgrass is stressed at high water temperatures (> 25˚C; Thom et al. 2014). Furthermore, salmon species are negatively impacted by increasing sea surface temperatures in early and late stages of their life cycle, which can lead to significant loss of thermal habitat area for Sockeye Salmon in the Fraser River Valley (Groulx et al. 2004).

Eelgrass (*Zostera marina*) meadows in Morro Bay, California, experience strong spatial differences in temperature, with colder waters occurring at the ocean-fed mouth and increasingly warmer waters towards shallower back of the bay. Seasonally, estuarine water temperature increases in the summer due to solar heating, and the ocean temperature at the mouth of the bay remains cooler due to wind-driven coastal upwelling (Walter et al. 2018). Morro Bay eelgrass meadows have declined by over 90% in area, and eelgrass beds are spatially variable, likely due to the thermal variation in the bay. However, Walter and colleagues (2018) concluded that while high temperature environments have been found to contribute to eelgrass wasting disease, low meristematic oxygen content and die-offs, it does not appear that recent abrupt temperature changes have contributed to the eelgrass population collapse in the bay.

2.2.3.5. Ocean acidification

Ocean acidification is the result of excess carbon dioxide entering marine waters and forming carbonic acid, acidifying water and lowering carbonate ion concentrations (Koweek et al. 2018). The increased acidity is a potential stressor for estuaries, pushing flora and fauna to their physiological limits. Depending on adaptive responses, acidification can hinder survivorship and alter the distribution and abundance of wetland species such as shellfish, shrimp and crab (Morzaria-Luna et al. 2014). Acidification can also have complex and wide-ranging ecological consequences, such as increasing primary productivity, decreasing Manila Clams, increasing Pacific Oyster, affecting predator-prey interactions (Reum et al. 2015), and increasing the bioavailability of trace metals from pollution (Robb 2014).

Some communities that occur within estuarine environments may have the ability to mitigate the effects of ocean acidification. Seagrass beds, which are highly productive, reduce water velocity, sequester carbon, and can export carbon to the deep ocean, suggesting they may be able to alter and mitigate acidification at the local scale (Koweek et al. 2018). However, a modeling study of Tomales Bay, California, suggested that seagrass metabolism is unable to provide long-term mitigation to ocean acidification (Koweek et al. 2018).

2.3. LINKING ACTIVITIES TO STRESSORS

Estuarine ecosystems encompass a mosaic of interconnected habitats, including seagrass, marsh, and sand flats, which together form a ‘seascape,’ supporting biodiverse communities of flora and fauna (e.g., fish species, Chalifour et al. 2019). Coastal development threatens estuarine ecosystems globally, through habitat degradation, land reclamation, shoreline modification, pollution (nutrient and waste runoff, and noise), and altered hydrology (Robb 2014; Chalifour et al. 2019). Habitat heterogeneity, biodiversity, and ecosystem services are negatively impacted and result in local species losses and successful species invasions (Casazza et al. 2021) through habitat modification and fragmentation (Robb 2014; Chalifour et al. 2019). The timeline of human development that is common to many estuaries includes disruption (including: mining, deforestation, agriculture, urbanization) in the watershed that increases sediment load, followed by dams, water diversions, and river management to reduce sediment input variability sediment supply, and the final stage of restoration of damaged habitats (Barnard et al. 2013).

Using the literature review described above and building off the list of activities and stressors compiled by previous analyses for the Pacific Region (Robb 2014; Hodgson et al. 2020) we provide a flow diagram showing the specific anthropogenic activities that occur in marine, terrestrial and atmospheric zones, and the flow of stressors from each activity. The stressors provided here are proximal to the activity, although we know that more distal stressors can be generated from anthropogenic activities that would influence estuary systems through time (e.g., changing ecological linkages in communities, or facilitating invasive species success).

Estuary systems are impacted by overlapping and diverse anthropogenic activities. The results of the literature review included 23 different anthropogenically driven activities (some broader activity groupings than others) and 16 stressors that negatively impact estuaries across the three zones (terrestrial, marine, atmospheric; Figure 2). Habitat modification, pollution, and sedimentation are the predominant stressors and are linked to the most anthropogenic activities, with habitat modification and sedimentation stemming from all three zones. Within the terrestrial zone, sedimentation and pollution are the predominant estuarine stressors. Within the marine zone, pollution and habitat modification predominate. Acknowledging the overlapping and interconnected nature of anthropogenic activities and their generated stressors has implications for restoration and understanding estuarine responses to anthropogenic disturbances. Where stressors are generated by multiple activities and from multiple zones, mitigating the effects of one activity may not be enough to avoid the impacts of the stressor in the system. This activity and stressor list were used to guide the selection of spatial data in the following Estuary Assessment.

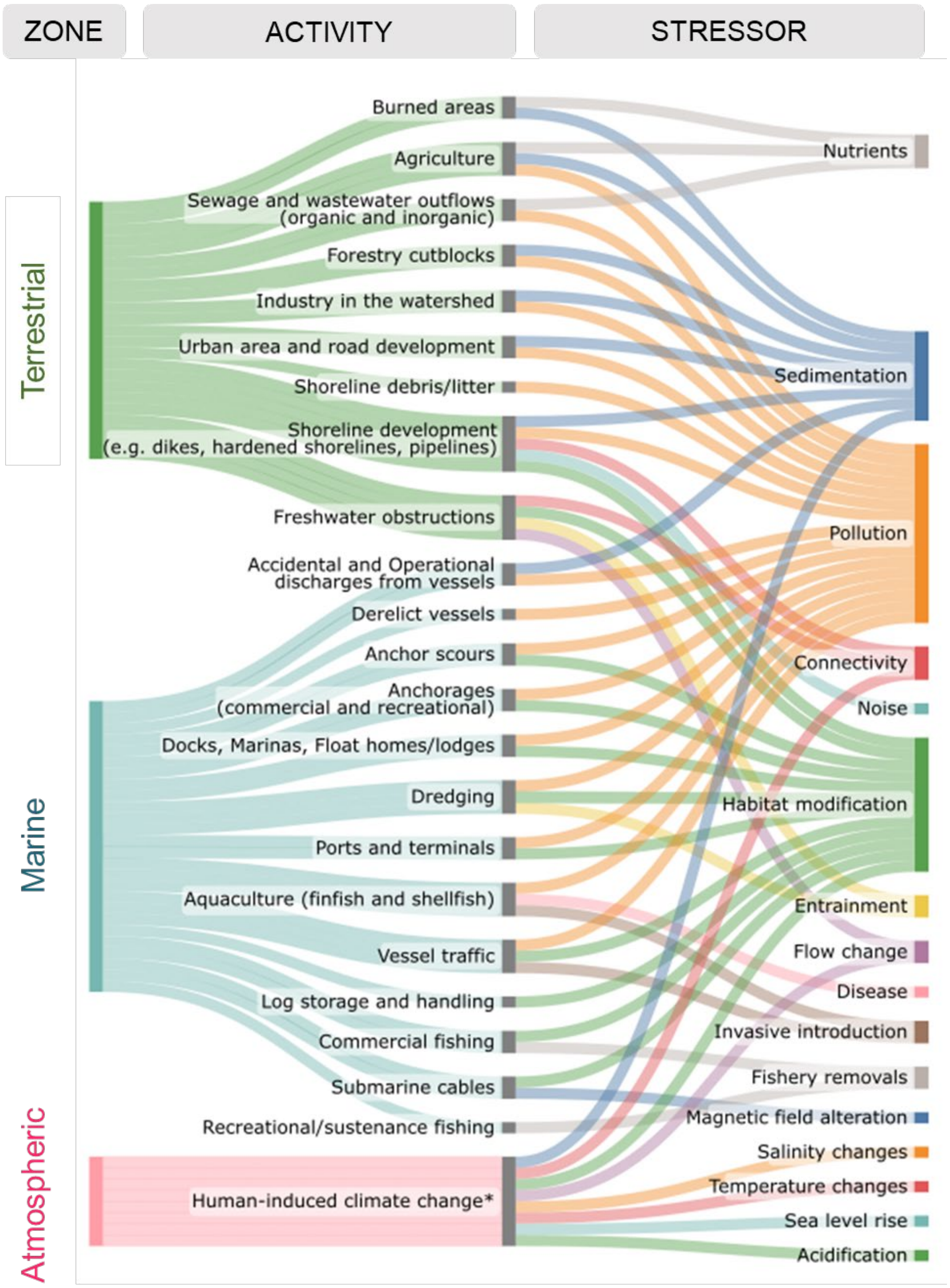

*Figure 2. Anthropogenic activities and their associated stressors with documented impacts on estuary systems that came out of the literature review described in this report. The list is not exhaustive and does not include activities or stressors outside of the literature review search parameters (e.g., activities identified in earlier research). For more information on the activities and associated stressors, see Section 2.2 (Anthropogenic Activities and Environmental Impacts) of this report. *Human-induced climate change arises from increased concentrations of greenhouse gases and the environmental stressors they generate in estuarine environments.*

3. ESTUARY ASSESSMENT METHODS

This analysis examines anthropogenic activities occurring in, or directly adjacent to, estuaries and within their upstream watersheds along the coast of BC.

3.1. STUDY AREA – ESTUARIES AND WATERSHEDS

Our analysis incorporated spatial data on 439 estuaries that were identified and mapped by the PECP (Ryder et al. 2007) and updated in 2019 (PBHJV Technical Team 2020) (Figure 3). The estuaries range in size from <0.01–200 km^2. Estuary polygons were delineated using a combination of provincial land classification maps (Terrain Resource Inventory Mapping [TRIM] base maps 1:20,000 scale) and stream data (Freshwater Atlas 1:20,000 scale), and were further refined using remotely sensed aerial, satellite and hydrographic data. Generally, estuary locations were first identified as the areas where the coastline and moderately sized streams (fourth order or greater) intersect. The specific estuary boundaries were then defined to incorporate the area from the intertidal zone lowest normal tide (0 chart datum contour line on Canadian Hydrographic Service (CHS) charts) up to a maximum of 500 m upstream, which was based on an estimated threshold of detectable surface salinity (Ryder 2007). Subtidal features were not included but the presence of physiographic features such as marsh, swamp and gravel bars from CHS charts and TRIM data helped delineate the boundaries of the intertidal areas. Care was taken to ensure the boundaries of an estuary did not extend into neighbouring areas fed by a different river or stream. Where aerial imagery was available, the freshwater plume extending from the stream was used to help confirm the seaward boundary of the estuaries. The criteria for delineating the boundaries of large estuaries (Skeena, Fraser, Nass) differed slightly from small estuaries due to large estuaries forming several intertidal deltas and having more upstream saltwater intrusion (see supplement in Ryder et al. 2007). PBHJV reported high certainty of capturing the location of large estuaries, however, given the varying map scales and imagery quality of the data used for delineating estuaries, as well as the fourth order stream minimum threshold, it is likely that the dataset underestimates estuary presence and does not include all small estuaries in BC (Ryder 2007; PBHJV Technical Team 2020). Further details on the mapping specifications are available from Ryder et al. (2007).

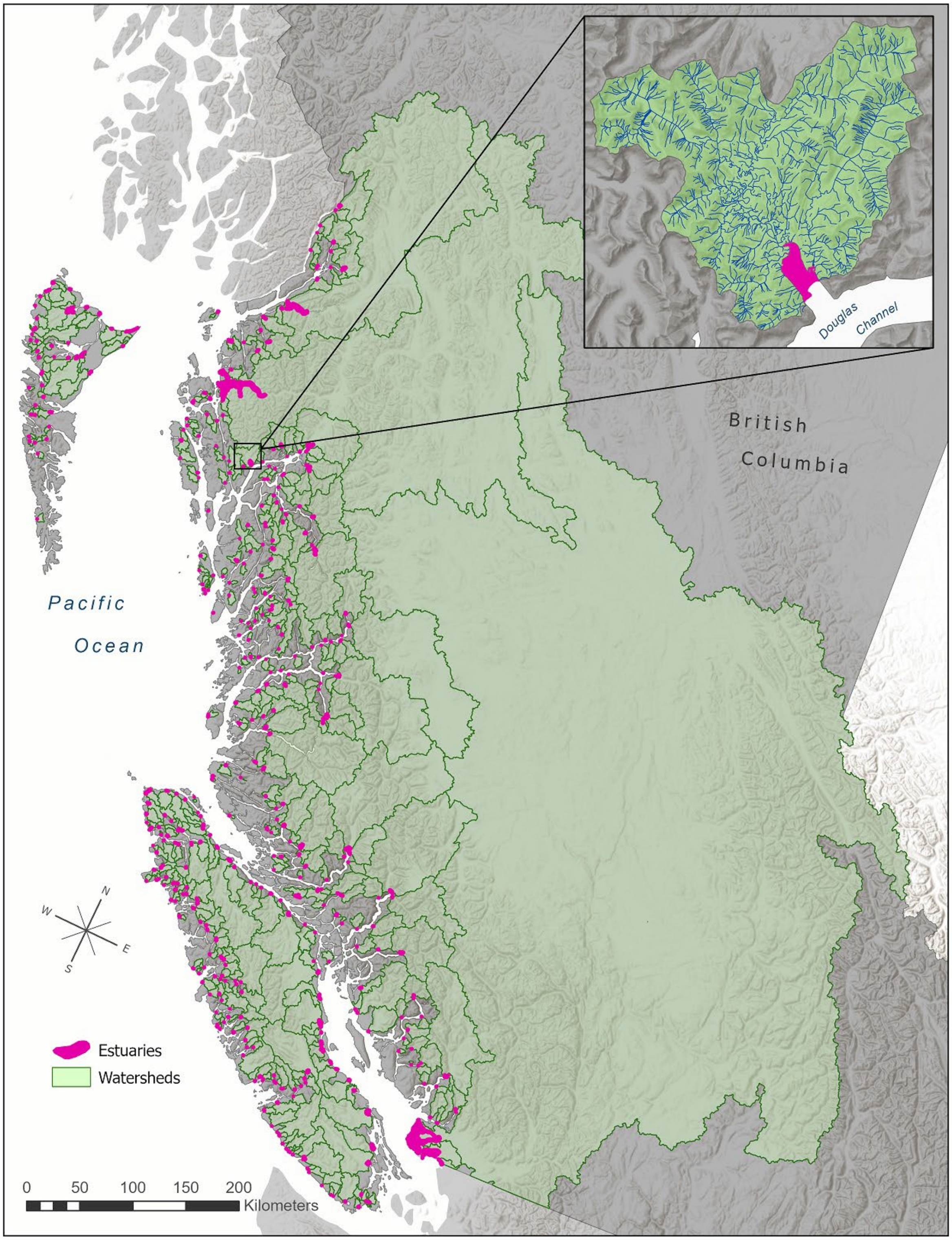

Figure 3. Estuaries and watersheds included in the analysis. The inset map shows an example of the high-resolution stream network data used to delineate the watersheds.

Assessing terrestrial activities that may indirectly impact an estuary (described in Section 2.2.1) required delineating the boundaries of the watersheds that flow into the estuaries given that activities occurring in a watershed can generate stressors that are transported to the estuary by river flow (e.g., sedimentation) (Thrush et al. 2004). We used stream data from the Freshwater Atlas of BC (GeoBc 2010) to compile a watershed polygon for each estuary. Each outflow stream segment overlapping an estuary was identified and a hierarchical code (FWA_WATERSHED_CODE) was used to link all upstream segments. Each stream segment has an associated fundamental watershed polygon which were combined based on the hierarchical code to produce one overall drainage basin watershed polygon per estuary. Watersheds ranged in size from small single-stream segment basins (< 15 ha), to large inland basins (> 20 million ha) with complex stream networks that extend beyond the Coast Mountain Range (e.g., Fraser River watershed) (Figure 3).

3.2. SPATIAL DATA COMPILATION

The literature review described above was used to guide the selection of spatial data to assess anthropogenic activities on estuary systems. Of the 23 activities and 16 associated stressors found to be detrimental to estuarine habitat from the review, spatial data were available for 28 (Figure 2), and more were added that were nested within the activities. For example, commercial fishing was broken out into particular fishing types, for a total of 44 spatial layers. The following subsections further describe the data layers chosen and how they were used in the analyses.

3.2.1. Terrestrial Zone

To quantify terrestrial stressors for estuaries, we calculated the overlap of activities occurring within a watershed or along the shoreline adjacent to an estuary. We assumed that the stressors generated by certain activities are transported by river or stream flow to the estuary (e.g., increased sedimentation from logged areas) (Thrush et al. 2004; Croke and Hairsine 2006; Bartley et al. 2014). In the case of activities occurring in the adjacent shoreline, which may not be part of the watershed for a given estuary, we assumed that the activity may directly overlap the estuary or that the activity is occurring close enough where a stressor is transported by surface or groundwater runoff (e.g., a road built directly on the shoreline). Similar to other estuary assessments (Greene et al. 2015), we considered the shoreline zone to be the area within 500 metres of the estuary. While the width of typical buffers to sensitive nearshore habitat varies (e.g., 30-100 m; Lemieux et al. 2004), we extended this distance to 500 m to capture the full footprint of coastal structures within neighbouring deltas and to account for any mismatches in map scales between the activity data and the coastline dataset we used. We did not consider the spread of terrestrial stressors in the marine environment beyond the downstream estuary. We also did not calculate activities in watersheds without estuaries, although we acknowledge that stressors may be transported from these watersheds to other estuaries via ocean currents.

Similar to the marine activities, most terrestrial activities did not have associated information on level of use and were thus quantified as the area of overlap with the watershed or shoreline zone. Exceptions include wastewater outflow (kg/year), freshwater obstructions (total points in watershed), and shoreline debris which is based on a modeled rating of debris potential. All totaled activity or stressor values, except the shoreline debris ratings, were normalized by watershed or shoreline zone area. This allowed us to compare values among watersheds, but it also functioned as a “dilution effect” in which the intensity of stressors generated in very large watersheds are likely reduced as they are transported to the estuary (Boyd et al. 2022). The watershed areas were log transformed (base 10) to generate a normal distribution of areas but also to create a more conservative dilution effect across the large range of watershed sizes (Figure C1).

3.2.2. Marine Zone

We assessed the activities identified through the literature review that had the potential to impact each estuary by quantifying the direct overlap of activities with estuaries as well as modeling the potential range of influence of a stressor generated by certain activities (e.g., pollution spreading from a point source), following approaches and incorporating datasets used in marine cumulative effects assessments (Ban et al. 2010; Clarke Murray et al. 2015). For most activities, we were only able to obtain presence information and therefore quantified the area of occurrence of the activity. For activities with information on level of use, such as commercial fishing and shipping, the potential impact was based on intensity values (i.e., total kg harvested, vessel counts, respectively) (Table 1).

For those activities for which the range of influence could be calculated (Table 1), the polygons or points representing the marine activity were buffered by their projected range of influence (if applicable) and rasterized to a 100 m grid with land acting as a barrier. The distance of influence for each activity were based on values from Robb (2014), Clarke Murray et al. (2015), and recent work by Agbayani and colleagues[3]. The full list of activities and range of influence distances are in Table 1. To simulate a distance-decay effect of a diffusing stressor, we adapted the approach followed in previous studies (Clarke Murray et al. 2015) and decreased the value of the stressor over 10 equal-width steps radiating out from the source, with each step reducing the original stressor value by 10%. We assigned a value of 100 to all cells within the original footprint of the area-based activity, and therefore at the maximum range of influence this value reduces to 10 within each cell. To not over-represent their potential impact, a distance-decay effect was not applied to those datasets mapped at a coarser scale, including the recreational fishing, commercial fishing, and shipping data.

The area-based or intensity values of raster cells overlapping an estuary were summed. The one exception was the stressor associated with aquatic invasive species point occurrences (e.g., European Green Crab trap surveys) which was summarized as species richness (i.e., the number of aquatic invasive species occurring in an estuary) following the approach used by Boyd et al. (2022). While invasive introduction is a stressor associated with various activities (e.g., vessel traffic), available spatial data were included based on advice from the regional peer review. To generate final activity values among estuaries, the summed values were normalized by dividing by estuary area.

3.2.3. Atmospheric Zone

We quantified four potential climate change related impacts to estuaries: sea level rise, precipitation change, air temperature change, and stream temperature change (Table 1). Future temperature and precipitation projections were based on the RCP 4.5 scenario developed by Wang et al. (2018). Due to the information available, sea level rise was based on the more extreme RCP 8.5 scenario using data from Natural Resources Canada. For all variables, we calculated the change between recent conditions (i.e., approximately early 21st century—years varied between datasets) to end-of-century predictions. Precipitation and air temperature data was modeled on a 1 km grid, stream temperature data was calculated at the point of outflow on the coast (Weller et al. 2023), and sea level rise was calculated for varying length segments of the coastline (~10–200 m). For all climate data, we averaged any values that overlapped with the estuaries.

*Table 1. Activity data per marine, terrestrial and atmospheric zones. Data sources noted as 'restricted' require a data request to the custodian for access. Unless noted in the geoprocessing notes column, the intensity of an activity was calculated as the area of overlap with an estuary. * Data associated with marine and terrestrial activities were included in the cluster analysis.*

Zone	Activity/Stressor	Data custodian	Data source	Date	Range of influence (km)	Geoprocessing notes
Marine*	Anchorages - commercial	Natural Resources Canada	Pending release	2022	2	–
	Anchorages - recreational	Fisheries and Oceans Canada	Open Data Canada - ACHARE	2022	0.5	–
	Anchor scours	Natural Resources Canada	Open Data Canada	2022	_	Buffer lines by 200 m.
	Aquaculture - finfish	Fisheries and Oceans Canada	Restricted	2011–2021	2	Calculate sum of market and restocking sales ($). Sum for all years. Join with tenure polygons.
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures	2022		Select records where the subpurpose is 'FIN FISH'. Only retain records with market values in DFO dataset.
	Aquaculture - shellfish	Fisheries and Oceans Canada	Restricted	2011–2021	2	Calculate sum of market and restocking sales ($). Sum for all years. Join with tenure polygons.
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures	2022		Select records where the subpurpose is 'SHELL FISH'. Only retain records with market values in DFO dataset.
	Aquatic invasive species	Province of BC - Ecosystems	BC Data Catalogue - Aquatic Invasive Species of BC	2012	_	Calculate as species richness overlapping estuaries.
		Fisheries and Oceans Canada	Gale et al. (2023). European Green Crab Surveys	2023	_	
	Commercial fishing - dive	Fisheries and Oceans Canada	Restricted	2016	_	Calculate as total kg per year Group records for: Green Sea Urchin, Red Sea Urchin, sea cucumber.
	Commercial fishing - hook and line	Fisheries and Oceans Canada	Restricted	2016	_	Calculate as total kg per year Group records for: Halibut, Sablefish, Lingcod, rockfish.
	Commercial fishing - prawn trap	Fisheries and Oceans Canada	Restricted	2016	_	Calculate as total kg per year Group records for: prawn and shrimp by trap.
	Commercial fishing - pressure hose	Fisheries and Oceans Canada	Restricted	2016	_	Calculate as total kg per year Group records for: Geoduck.

Zone	Activity/Stressor	Data custodian	Data source	Date	Range of influence (km)	Geoprocessing notes
	Commercial fishing - trawl	Fisheries and Oceans Canada	Restricted	2016	–	Calculate as total kg per year Group records for: bottom trawl, midwater trawl, shrimp by trawl.
	Commercial fishing - salmon gill net	Fisheries and Oceans Canada	Restricted	2016	–	Calculate as total kg.
	Commercial fishing - salmon seine	Fisheries and Oceans Canada	Restricted	2016	–	Calculate as total kg.
	Commercial fishing - salmon troll	Fisheries and Oceans Canada	Restricted	2016	–	Calculate as total kg.
	Derelict vessels	Transport Canada	Restricted	2018	0.5	–
	Disposal at sea	Environment and Climate Change Canada	Open Data Canada - Active and Inactive Disposal at Sea	2018	2	–
	Docks	Fisheries and Oceans Canada	Open Data Canada - Floating structures	2018	0.5	–
	Dredging	Environment and Climate Change Canada	Restricted - dredging for disposal at sea; dredging for re-use or alternate disposal or management not included	2020	–	–
		Fisheries and Oceans Canada (FFHPP)	Restricted - Program Activity Tracking for Habitat (PATH)	2023	–	Extracted records where the primary impact is "Dredging/Excavating". Buffered points by 50 m prior to combining with ECCC data.
	Floating homes/Lodges	Fisheries and Oceans Canada	Open Data Canada - Floating structures	2018	2	–
	Log handling	Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures	2022	2	Select records where the tenure subpurpose is 'LOG HANDLING/STORAGE'.
		Province of BC - GeoBC	BC Data Catalogue - Coastal BC Marine Industrial Sites	1998		Selected records where the description is 'Log Booming', 'Log Booms', 'Log Dump', 'Log Dump/Sort'. Points were buffered by 1 m before combining with Tenures data.
	Marinas	Fisheries and Oceans Canada	Open Data Canada - Floating structures	2018	2	–

Zone	Activity/Stressor	Data custodian	Data source	Date	Range of influence (km)	Geoprocessing notes
	Ports and Terminals	Province of BC - GeoBC	BC Data Catalogue - BC Ports and Terminals	2016	2	Selected only large ports that were not included in the docks dataset.
	Recreational boating	Transport Canada	Restricted	2022	2	Calculate as total predicted boats.
	Recreational/sustenance fishing - anadromous	BC Marine Conservation Atlas	BC Marine Conservation Atlas - Sport Fishing	2011	–	–
	Recreational/sustenance fishing - crab	BC Marine Conservation Atlas	BC Marine Conservation Atlas - Sport Fishing	2011	–	–
	Recreational/sustenance fishing - groundfish	BC Marine Conservation Atlas	BC Marine Conservation Atlas - Sport Fishing	2011	–	–
	Recreational/sustenance fishing - prawn	BC Marine Conservation Atlas	BC Marine Conservation Atlas - Sport Fishing	2011	–	–
	Underwater infrastructure (submarine cables)	Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures	2022	–	Select records where the tenure subpurpose is 'ELECTRIC POWER LINE', 'SCIENCE MEASUREMENT/RESEARCH', 'SEWER/EFFLUENT LINE', 'TELECOMMUNICATION LINE', or 'WATER LINE'. Polygon data, no buffer.
	Vessel traffic	Transport Canada	Restricted	2021	30	Calculate as total count of vessels per year.
Terrestrial*	Agriculture	Esri, Impact Observatory, Microsoft	Esri - Sentinel-2 Land Use	2022	–	Select pixels classified as "crops".
	Burned areas	Province of BC - BC Wildfire Service	BC Data Catalogue - Fire Perimeters	2022	–	Select records where the burn year is 2013–2022.
	Dams	Province of BC – Freshwater Atlas	BC Data Catalogue-Freshwater Atlas Obstructions	2022	–	Select features where obstruction type is "dam".
	Forestry cutblocks	Province of BC - Forest Analysis and Inventory	BC Data Catalogue - Harvested Areas of BC	2022	–	Select records where the harvest year is within the past 10 years - the typical minimum time for a stand to meet free-growing criteria (Forest Practices Board 2006).
	Freshwater obstructions	Province of BC – Knowledge Management	BC Data Catalogue-PSCIS Fish Habitat Confirmations	2022	–	–

Zone	Activity/Stressor	Data custodian	Data source	Date	Range of influence (km)	Geoprocessing notes
		Fisheries and Oceans Canada (FFHPP)	Restricted - Program Activity Tracking for Habitat (PATH)	2023	–	Selected records where the primary impact is 'Changes in Flows/Water Levels', 'Fish Passage', or 'Watercourse Alteration'.
	General development of shoreline (500 m inland)	Esri, Impact Observatory, Microsoft	Esri - Sentinel-2 Land Use	2022	–	Select pixels classified as "Built Area".
		Province of BC - GeoBC	BC Data Catalogue - Digital Road Atlas	2017	–	Buffer individual lanes by 2.5 m.
		Province of BC - Forest Tenures Branch	BC Data Catalogue - Forest Tenure Road Segment Lines	2008	–	Buffer by 5 m.
		Natural Resources Canada	Open Data Canada - National Railway Network	2021	–	Buffer by 5 m.
		Province of BC - Water Management	BC Data Catalogue - Flood Protection Structural Works	2004	–	Buffer by 10 m.
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures	2022	–	Select Industrial records except Mining and Log Handling.
		Province of BC - GeoBC	BC Data Catalogue - Coastal BC Marine Industrial Sites	1998	–	Selected records that are not associated with Log Handling.
		Coastal and Ocean Resources	ShoreZone	2020	–	Select manmade structures and buffer by 10 m.
		Province of BC - Economics and Trade Branch	BC Data Catalogue - BC Major Timber Processing Facilities	2018	–	Buffer points by 100 m.
		BC Energy Regulator	Pipeline segments and rights-of-way	2022	–	Buffer segments by 2.5 m.
	General industry in watershed	Province of BC - Economics and Trade Branch	BC Data Catalogue - BC Major Timber Processing Facilities	2018	–	Buffer points by 100 m.
		Province of BC - Health Safety and Permitting	BC Data Catalogue - Permitted Mine Areas	2020	–	–
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures	2022	–	Select Industrial records except Mining and Log Handling.
		Province of BC - GeoBC	BC Data Catalogue - Coastal BC Marine Industrial Sites	1998	–	Selected records that are not associated with log handling.
		BC Energy Regulator	Pipeline segments and rights-of-way	2022	–	Buffer segments by 2.5 m

Zone	Activity/Stressor	Data custodian	Data source	Date	Range of influence (km)	Geoprocessing notes
	General development in watershed (not including shoreline area)	Esri, Impact Observatory, Microsoft	Esri - Sentinel-2 Land Use	2022	–	Select pixels classified as "Built Area".
		Province of BC - GeoBC	BC Data Catalogue - Digital Road Atlas	2017	–	Buffer individual lanes by 5 m.
		Province of BC - Forest Tenures Branch	BC Data Catalogue - Forest Tenure Road Segment Lines	2008	–	Buffer by 5 m.
		Natural Resources Canada	Open Data Canada - National Railway Network	2021	–	Buffer by 5 m.
	Mining	Province of BC Geological Survey	BC Data Catalogue – MINFILE Production Database	2020	–	Calculate as tonnes mined.
	Sewage and wastewater outflows (organic)	Environment and Climate Change Canada	Pollutants Affecting Whales and their Prey Inventory Tool	2018	–	–
	Sewage and wastewater outflows (inorganic)	Environment and Climate Change Canada	Pollutants Affecting Whales and their Prey Inventory Tool	2018	–	–
	Shoreline debris/litter	Province of BC - Environmental Protection Division	BC Data Catalogue - PICES 5km Debris Ratings	2015	–	Average debris rating (0: no debris – 5: significant debris along entire beach) of 5 km line segments that overlap each estuary.
Atmospheric	Air temperature change	University of British Columbia - Wang et al.	ClimateBC	1981–2099	–	RCP 4.5 scenario, difference in summer mean temperature.
	Precipitation change	University of British Columbia - Wang et al.	ClimateBC	1981–2099	–	RCP 4.5 scenario, difference in mean annual precipitation.
	Sea level rise	Natural Resources Canada	Open Data Canada - CanCoast	2006–2099	–	RCP 8.5 scenario, average sea level rise (m) of lines overlapping each estuary.
	Stream temperature change	Fisheries and Oceans Canada	Weller et al. (2023)	1981–2100	–	RCP 4.5 scenario, difference in August mean temperature.

3.3. CLUSTER ANALYSIS

To better understand which estuaries may be impacted by similar anthropogenic activities and associated stressors, we performed a cluster analysis to group estuaries based on the frequency and magnitude of activities. The cluster analysis and evaluations of the outputs were all conducted in R (R Core Team 2022). The cluster analysis was based on the activity data for estuaries described above, building on past analyses (Merrifield et al. 2011; Robb 2014). It consisted of the 41 marine and terrestrial activities. The spatial data within the atmospheric zone were not included given that they represent pervasive stressors associated with pollution that may be generated by some of the marine and terrestrial activities mapped separately. These data were instead compared to the resulting clusters in a series of scatterplots. Because the activity data tended to be right skewed and contained zeros, all values were transformed prior to our analyses using the inverse hyperbolic sine (IHS; Burbidge et al. 1988). We then standardized all values by subtracting by the mean and dividing by the standard deviation.

We used hierarchical clustering to define groups of estuaries with similar anthropogenic activities. We chose to conduct our clustering based on the Ward D2 method using Canberra distances (Lance and Williams 1967) as this method emphasizes low within-group dispersion, thus producing compact spherical clusters of estuaries (Murtagh and Legendre 2014). We selected the number of clusters using internal validation based on 22 indices for determining the best number of clusters, calculated using the NbClust R package (Charrad et al. 2014). We chose the final number of clusters as the number between 4 and 12 that was selected by the most indices. This range was determined as having enough clusters to be useful for distinguishing the estuaries and small enough to be useful for interpretation. To visualize the multivariate relationship between the activity data and the selected clusters, we used a principal components analysis (PCA) using the vegan package (Oksanen et al. 2022) in R (R Core Team 2022).

To differentiate how the clusters are broadly defined by the activities, we applied multilevel pattern analysis using the indicspecies R package (De Cáceres and Legendre 2009). This method is commonly applied to identify indicator species for different ecological community types (De Cáceres et al. 2010), but here we are assessing the activities as indicators of each cluster. The method chooses the highest association between each activity and the clusters and then tests the association for statistical significance ($p = 0.05$). Only significant associations are retained as indicators of the clusters. We chose to restrict the associations between activities and single clusters, although the method can also assess the association with groups of clusters. Thus, while this indicator analysis captures the highest associations it does not provide information about whether the activities also occur in estuaries in other clusters.

3.4. FISH AND FISH HABITAT EVALUATION

In addition to an assessment of activities and stressors relevant to estuaries, information was requested on the estuaries important for salmon and other significant fish and invertebrate species, and the presence of sensitive fish habitat within estuaries. To compile a list of species and habitat types within estuaries, we used the DFO definition for Ecologically Significant Species (ESS; DFO 2006) and a recent application of the ESS criteria on Pacific marine fishes, invertebrates, plants, and algae (Gale et al. 2019). We then compared the list to species and habitats documented within estuary management plans, where available, supplemented with species inventories specific to the estuaries from technical reports and scientific literature (Table 2). These data were used to guide the compilation of relevant spatial datasets. Dungeness Crab were not identified as Ecologically Significant by Gale et al. (2019) but were included based on recommendations at the regional peer review meeting given the important ecological role the species plays in estuaries. A list of additional species noted in estuary management plans that may play important roles in estuarine systems but that have not been assessed as Ecologically Significant according to the DFO criteria was also compiled (Appendix D).

*Table 2. Estuarine species and habitats documented in estuary management plans for BC and identified as Ecologically Significant Species (ESS) from past assessments, including associated ESS criteria scores (Gale et al. 2019). Species were considered Ecologically Significant if they scored high (2) for any of the ecological roles assessed. ^ Dungeness Crab were not identified as Ecologically Significant by Gale et al. (2019) but have been included here based on recommendations at the peer review meeting given the important ecological role of Dungeness Crab in estuaries. * denotes species where sufficient spatial data were available within the estuary polygons to allow assessment in this report.*

Common Name	Scientific Name	ESS Criteria Score	Campbell River Estuary	Courtenay Estuary	Cowichan -Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary
Fish Species									
Big Skate	*Raja binoculata*	2 (upper-level)	–	–	–	X	–	–	–
Chinook Salmon*	*Oncorhynchus tshawytscha*	2 (upper-level, nutrient transport), 1 (forage)	X	X	X	X	X	X	X
Chum Salmon*	*Oncorhynchus keta*	1 (upper-level, forage), 2 (nutrient transport)	X	X	X	X	X	X	X
Coho Salmon*	*Oncorhynchus kisutch*	2 (upper-level, nutrient transport), 1 (forage)	X	X	X	X	X	X	X
Cutthroat Trout	*Oncorhynchus clarkii*	2 (upper-level), 1* (forage), 1 (nutrient transport)	X	X	X	X	X	X	X
Dolly Varden	*Salvelinus malma lordi*	2 (upper-level)	X	–	X	X	–	X	X
Eulachon*	*Thaleichthys pacificus*	2 (forage, nutrient transport)	–	–	–	X	–	–	X
Green Sturgeon	*Acipenser medirostris*	1 (upper-level, nutrient transport)	–	–	–	X	X	–	–
Lingcod	*Ophiodon elongatus*	2 (upper-level)	–	X	–	X	X	–	–
Longnose Skate	*Raja rhina*	2 (upper-level)	–	X	–	–	–	–	–
Pacific Hake	*Merluccius productus*	2 (upper-level), 1 (forage, nutrient transport)	–	–	–	–	–	X	–
Pacific Herring*	*Clupea pallasii*	2 (forage, nutrient transport)	X	X	X	X	X	X	X
Pacific Sand Lance*	*Ammodytes hexapterus*	2 (forage)	–	X	–	X	X	X	X
Pink Salmon*	*Oncorhynchus gorbuscha*	1 (upper-level), 1* (forage), 2 (nutrient transport)	X	X	–	X	X	X	X
Shiner Perch	*Cymatogaster aggregata*	2 (forage)	–	X	–	X	X	X	X
Sockeye Salmon*	*Oncorhynchus nerka*	1 (upper-level, forage), 2 (nutrient transport)	X	X	–	X	X	X	–
Spiny Dogfish	*Squalus suckleyi*	2 (upper-level), 1 (nutrient transport)	–	X	–	X	–	–	X
Steelhead	*Oncorhynchus mykiss*	2 (upper-level), 1* (forage), 1 (nutrient transport)	X	X	X	X	X	X	X

Common Name	Scientific Name	ESS Criteria Score	Campbell River Estuary	Courtenay Estuary	Cowichan -Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary
Surf Smelt	*Hypomesus pretiosus*	2 (forage)	–	X	–	X	–	–	X
Walleye Pollock	*Theragra chalcogramma*	2 (upper-level, forage)	–	–	–	X	–	X	–
Invertebrate Species									
Bay Ghost Shrimp	*Neotrypaea californiensis*	–	–	X	–	X	X	X	–
Coonstripe/Dock Shrimp	*Pandalus danae*	–	–	–	–	–	–	–	X
Dungeness Crab^*	*Metacarcinus magister*	–	–	X	–	X	X	–	X
Horse Clam/Fat Gaper	*Tresus capax*	–	–	–	–	–	X	–	–
Horse Clam/Pacific Gaper	*Tresus nuttallii*	–	–	–	–	–	X	–	–
Littleneck Clam	*Leukoma staminea*	–	–	–	–	–	X	X	–
Littorina Snails	*Littorina sp.*	–	–	X	–	–	–	–	–
Nuttall’s Cockle	*Clinocardium nuttallii*	–	–	X	–	–	X	X	–
Ochre Sea Star	*Pisaster ochraceus*	–	–	X	–	–	–	–	–
Spot Prawn*	*Pandalus platyceros*	–	–	–	–	–	–	X	–
Sunflower Sea Star	*Pycnopodia helianthoides*	–	–	X	–	–	–	–	–
Zooplankton	e.g., Calanoid copepods, Harpacticoid copepods, Euphausiids	–	X	–	X	X	X	–	X
Habitats									
Eelgrass*	*Zostera marina*	–	X	X	X	X	X	–	X
Macroalgae*	Multiple species	–	X	X	–	–	–	X	X
Channels	–	–	X	–	X	–	X	X	X
Gravel bar/reef*	–	–	–	–	–	–	X	X	X
Mudflats*	–	–	X	X	–	X	X	X	X
Salt or tidal marshes*	Multiple species	–	X	X	X	X	X	X	X
Sand flats*	–	–	X	X	–	X	X	X	X

Sources: Campbell River estuary (Bell and Thompson 1977; Penfold 2002); Courtenay estuary (Asp and Adams 2000; Hamilton et al. 2008; Property Services Branch 2011); Cowichan-Koksilah estuary (Lambertson 1987; Hillaby 1991); Fraser estuary (Greer et al. 1981; Levings 1983; FREMP 2003; Kehoe et al. 2021; Chalifour et al. 2019); Nanaimo estuary (Catherine Berris Associated Inc. 2006); Somass estuary (Catherine Berris Associated Inc. 2004); Squamish estuary (Province of BC and Government of Canada 1981; Squamish Estuary Coordinating Committee 1999); Skeena estuary (Sharpe et al. 2021); Coastwide (Jeffery et al. 2023).

Spatial data were compiled for species considered Ecologically Significant and the suite of marine habitat types mentioned in at least one of the existing estuary management plans for BC. Spatial data relevant to estuaries were not available for all species or habitats. For example, data available for Longnose Skate originate from research surveys that do not operate within estuarine environments, and data for many invertebrate species are from surveys with inadequate survey coverage. Where data were available, data processing for the relevant species and habitats were overlaid to calculate their prevalence within each estuary and then compared to the activity counts in a series of scatterplots. Similar to the activity data, there was no ranking of importance among species data. We compared ecological data to activities not to suggest a causal relationship, but instead to identify ecologically important estuaries that may be under threat.

3.4.1. Salmon

Pacific salmon are a key component of marine and coastal ecosystems in BC and are of high ecological, cultural, and economic importance. As noted previously, salmon were identified as ESS due to their role transporting nutrients between marine, coastal and terrestrial ecosystems, and their importance as both prey and predators species (Gale et al. 2019). Salmon escapement biomass and richness were calculated using information on adult salmon returning to spawn (termed “escapements”) from the New Salmon Escapement Database System (NuSEDS; DFO 2022) based on records for the five species of salmon included in Canada’s Policy for the Conservation of Pacific Wild Salmon (Wild Salmon Policy, DFO 2005), i.e., Coho, Chinook, Chum, Pink, and Sockeye Salmon. For biomass, the average maximum escapement for each salmon population was calculated using data from 1990–2020 (fall) to align with the reported ecosystem regime shift in salmon abundance in 1989 (Irvine and Fukuwaka 2011). For each species, the average maximum escapement was summed by population within the principal drainage areas and coastal rivers and linked to spatial data on the BC’s stream network from the Freshwater Atlas (Gray 2010). The streams were intersected with the estuary polygons and, for each estuary, the escapement was summed, by species, for all upstream populations and multiplied by the average weight for each species. The resulting values were then summed across all species to produce a total estimate of biomass in kilograms (kg). Species richness was calculated as the number of Pacific salmon species that had been recorded in rivers and streams flowing through the estuary, but differentiating between even and odd years of Pink Salmon as two separate species for a maximum possible richness of six. Sufficient spatial data were not available for Dolly Varden, Cutthroat Trout, and Steelhead to allow further assessment.

To estimate salmon diversity, we also calculated the number and status of conservation units (CUs) of Pacific salmon present in each watershed associated with an estuary. As one of six strategies within the WSP, CUs have been developed for Chinook, Chum, Coho, Pink, and Sockeye Salmon to represent important elements of salmon biodiversity for conservation and management (DFO 2009a). A CU is defined as a “group of wild salmon sufficiently isolated from other groups that, if extirpated, is very unlikely to recolonize naturally within an acceptable timeframe” (DFO 2005). The conservation status of CUs has been evaluated using various biological metrics and CUs are classed as Red (poor, at risk of extirpation), Amber (marginal) and Green (healthy) (Holt et al. 2009). The spatial scale of the CUs varies by salmon species and CUs for some species extend across several watersheds while others are more localized. For each estuary, we totaled the CUs (represented as polygon data) overlapping the associated watershed and generated a count of CUs for each conservation status class.

3.4.2. Forage Fish

Forage fish are species that are not at the top of the marine food chain but are an important food source for other species and experience high mortality due to predation (DFO 2009d). Estuarine fishes that have been identified as Ecologically Significant due to their role as forage species include Eulachon, Pacific Herring, Pacific Sand Lance, Surf Smelt, and Shiner Perch (Gale et al. 2019). Based on available spatial datasets, the presence of Eulachon, Pacific Sand Lance suitable habitat, and Pacific Herring spawn biomass was determined for each estuary. Sufficient spatial data were not available to develop layers for Surf Smelt and Shiner Perch. Eulachon Important Areas were identified as the estuaries downstream of streams known to be important for spawning and rearing, which typically occurs between February and May[4].

Pacific Sand Lance habitat data were derived from two habitat suitability models that used environmental variables (e.g., bathymetry, rugosity, tidal current, distance to estuaries) to predict locations of probable sand lance habitat within the Strait of Georgia. Robinson et al. (2021) used a ~50m raster cell size and generated a prediction surface representing burying habitat to a 150 m depth. (Huard et al. 2022) used a 20m cell size and generated spawning habitat predictions for the intertidal zone. For each model, we calculated the mean probability for all raster cells overlapping each estuary. While an estuary's influence on sand lance habitat may expand beyond the extent of the estuary (Huard et al. 2022), we did not have informed estimates of this range of influence and therefore only incorporated values overlapping the estuary. Huard et al. (2022) found that distance to estuaries was the strongest predictor of sand lance spawning habitat, with higher likelihood of habitat closer to estuaries. However, because very fine sediments can clog the gills of fish, they found a low likelihood of suitable habitat in the portion of estuaries with fine silts (Huard et al. 2022), and therefore the estuaries themselves may not always be the most suitable habitat but may be important sources of the sediments in adjacent areas.

Pacific Herring spawn biomass was calculated using survey data from the Herring Spawn Index (Grinnell et al. 2023). We included survey data from 1988–2003 as this is when dive surveys were implemented to complement surface surveys. Surveys were conducted from February to April when herring typically spawn (Grinnell et al. 2023). To associate the herring spawn data with estuaries, we buffered the centroid of each spawning event by half the observed length of the spawning event to generate polygons for each spawning observation. We removed the portions overlapping land from these locations and removed any polygons that became disconnected from the original centroid point. While the shape of the polygons would not represent the true shape of the spawning event, the buffer operation allows us to estimate the general proximity of an estuary to a spawning location. The biomass values of each spawning event were then associated with the estuaries overlapping the polygons. In the Herring Spawn Index, egg biomass is observed at the surface layer, and on canopy and understory kelp. For the spawning polygons overlapping an estuary, we summed the values for all observation layers (surface, macro, and understory; M. Thompson, pers comm.) to get the biomass of each spawning event and then summed all events to get the total yearly biomass. We then calculated the overall mean biomass per year associated with each estuary.

3.4.3. Invertebrates

Of the invertebrate species deemed ecologically significant in the NSB (DFO 2017), we only analyzed the presence of Dungeness Crab (*Metacarcinus magister*) and Spot Prawn (*Pandalus*

[4] DFO. 2016. Important Areas for Eulachon – spawning. File geodatabase feature class.

platyceros) in estuaries. The other invertebrate species did not have adequate spatial data across the suite of estuaries due to limited coverage of survey data and commercial catch data. While not identified as Ecologically Significant at a bioregion-wide scale, within estuaries Dungeness Crab play an important role as opportunistic predators of shrimps, gastropods and bivalves, and may also feed on fish such as Lingcod, Pacific Sanddab and Longfin Smelt (Gale et al. 2019). Spot Prawn are considered ecologically significant due to their role as an important forage prey species for many fish species such as flatfish, rockfish, Pacific Hake and skates (Gale et al. 2019).

The presence of Dungeness Crab was derived from a species distribution model based on survey and commercial catch data and with a 0.5-km spatial resolution (Nephin et al. 2023). We averaged probability values of raster cells overlapping each estuary. Data on Spot Prawn was extracted from survey and commercial catch data in DFO shellfish databases. Spot Prawn was considered present in an estuary if any observation was within 500 metres of an estuary.

3.4.4. Estuarine Habitats

3.4.4.1. Eelgrass

Eelgrass beds provide refuge from predation, foraging, and nursery habitats for marine fish including juvenile Pacific salmon, Shiner Perch, and forage fish (Sharpe et al. 2019). They are also an important spawning substrate for Pacific Herring (Fox et al. 2018). Eelgrass beds also provide an algal food source and biogenic habitat for multiple trophic levels of epifaunal and infaunal invertebrates that are prey for forage fish and salmon (Murphy et al. 2021). Eelgrass beds also contribute organic detritus that forms the base of the food web within estuaries (Quinn 2018).

We determined the presence of eelgrass in estuaries using two datasets: one dataset that records observations of the coastline as linear features (termed “biobands”), and another that maps polygons of eelgrass beds using various methods of observation. Given the differing geometries as well as the differing survey methodologies and completeness of the datasets, we did not combine them in any way, and instead compared their overlap with estuaries individually.

The linear eelgrass features were derived from the Shorezone Coastal Imaging and Habitat Mapping dataset (Cook et al. 2017). In the Shorezone dataset, eelgrass, among other habitat types, is identified from aerial imagery. Coastwide coverage is achieved by compiling observations collected over the past three decades (1991–2022). We selected all lines that contain eelgrass observations (recorded as “patchy” or “continuous”) and that are within 100 m of an estuary. Where observations from different years overlap, we selected the lines from the most recent records so as not to double-count. Shorezone observations are made for the subtidal, intertidal and supratidal zones, resulting in three coincident linear features. Where eelgrass was observed in the subtidal and intertidal zones, we retained both lines. We summed the length of all lines overlapping each estuary and normalized the total by estuary area.

The eelgrass polygon dataset contains observations from a variety of government and non-governmental sources[5]. Eelgrass beds were mapped using direct and remotely sensed observations (e.g., dive surveys, aerial imagery). We calculated the area of overlap of eelgrass polygons with the estuary polygons and normalized the total per estuary by estuary area.

[5] Beatrice Proudfoot, Ashley Park and Carrie Robb. 2022. Eelgrass polygon data for the BC coast to 2022. Unpublished data.

3.4.4.2. Macroalgae

Similar to eelgrass, macroalgae also provide foraging, nursery, and refuge habitat for a variety of juvenile and adult fishes such as Pacific salmon and rockfish species, as well as a diverse group of invertebrate species (Graham 2004; Sharpe et al. 2019). Habitat structure is provided in the form of brown canopy kelps (*Nereocystis luetkeana* – Bull Kelp, *Macrocystis pyrifera* – Giant Kelp) and various brown and green understory and intertidal kelps (e.g., *Saccharina latissima, Ulva lactuca*) (Trebilco et al. 2015). Macroalgae species contribute detritus to support the base of the estuarine food web (Quinn 2018). We compiled spatial data in the form of polygons and bioband linear features for brown canopy and understory kelps and green macroalgae.

Using the Shorezone dataset and methods described in Section 3.4.4.1 (Eelgrass), we extracted and combined linear features for Bull Kelp and Giant Kelp to generate a brown canopy kelps bioband dataset. We then created an understory and intertidal brown kelps bioband dataset (classified in Shorezone as “soft brown kelps” and “dark brown kelps” which encompassed observations of numerous species, e.g., *Saccharina latissima*, *Saccharina groenlandica*). Lastly, we selected observations of *Ulva lactuca* to generate a green macroalgae bioband dataset.

Polygon datasets of Bull Kelp and Giant Kelp were combined to create a brown canopy kelp polygon dataset (British Columbia Marine Conservation Analysis (BCMCA) Project Team 2011). Canopy kelps are not expected to intersect the intertidal zone; however, their proximity to estuaries and connectivity to intertidal habitats make them relevant to this analysis. Similar to the eelgrass polygons, the kelp polygons were collected by numerous organizations using different methodologies and at various points in time. Each of the bioband and polygon datasets were intersected with the estuary polygons to measure overlap. The length of the bioband lines in an estuary were summed and divided by estuary area, and the polygon feature overlap area was also normalized by estuary area.

3.4.4.3. Salt marsh

Salt marshes occur in the upper intertidal zone and support a diverse range of bird, fish, invertebrate and mammal species. Salt marshes are dominated by brackish water tolerant plants that provide habitat structure for important fish species such as juvenile Pacific salmon, Shiner Perch, and Surf Smelt, as well as for a prey trophic level of small invertebrates (e.g., amphipods, polychaetes, molluscs) (Chalifour et al. 2019; Lefcheck et al. 2019; Sharpe et al. 2019). Similar to the methodology in Section 3.4.4.1 (Eelgrass), we extracted bioband linear features from the Shorezone database based on the salt marsh codes ‘SAMA’ and ‘SAMB’. Salt marshes were identified by the presence of salt tolerant shrubs and grasses such as *Salicornia virginica* and *Puccinellia* spp. We summed the length of all salt marsh lines overlapping each estuary and normalized the total by estuary area.

Availability of spatial data representing tidal marshes is more limited. This band of vegetation, characterized by species such as *Carex lyngbyei,* typically occurs above salt marsh vegetation around estuaries and is associated with freshwater. Tidal marshes can be extensive in some estuaries (e.g., Fraser estuary (Groulx et al. 2004)). We separately extracted bioband linear features from the Shorezone database for the ‘SEDG’ classification to represent tidal marshes.

3.4.4.4. Sand, mud, mixed, and hard substrates

In addition to biogenic habitats (e.g., eelgrass, kelp), the varied substrate types of an estuary are also important for and indicative of different species assemblages. Soft sediments (e.g., sand/mud banks and flats) are important infaunal invertebrate habitat, forage fish spawning and burying habitat, and low tide refuge for juvenile salmon (Levings 1982; Archambault et al. 2010;

Sharpe et al. 2019; Huard et al. 2022). Hard substrates in the intertidal (e.g., gravel and rocky reefs) provide refuge structure for forage fish and surf perches, and they support sessile communities of invertebrates (Toft et al. 2007; Gregr et al. 2013). To represent these habitats, we used a high resolution raster dataset (20 m cell size) of substrate type that was compiled using various biophysical survey datasets (Gregr et al. 2021). From the raster dataset, we generated individual datasets of sand, mud, mixed and hard substrate. We calculate the area of overlap of each dataset with the estuary polygons and normalized by estuary area. The substrate dataset did not completely overlap every estuary due to the estuary polygons extending farther upstream into freshwater beyond the extent of the exclusively marine substrate dataset. However, this difference in overlap was minimal and not significantly different among estuaries.

3.4.4.5. Rugosity

Rugosity—a measure of surface roughness calculated as the contoured area divided by the planar area—can be used to indicate the structural complexity of the substrate (Du Preez 2015). Diversity and richness are generally positively correlated with habitat complexity (Tews et al. 2004; Kovalenko et al. 2012), and high rugosity has been shown to increase fish community biomass (Trebilco et al. 2015) and invertebrate community diversity (Loke and Todd 2016). As a continuous measurement, rugosity complements the categorical observations of the substrate data. We used a raster dataset of rugosity with a 20 m spatial resolution (Gregr et al. 2021) derived from bathymetry charts from the Canadian Hydrographic Service (CHS), and we averaged the rugosity values overlapping each estuary.

3.4.4.6. Biogenic habitat richness

The diversity of intertidal habitats present in an estuary can influence species and community diversity (Nagelkerken et al. 2015; Chalifour et al. 2019; Seitz et al. 2020). For example, the arrangement and connectivity of habitat types such as kelp and seagrass can influence the movement of fish and enhance the nursery function of seagrass (Olson et al. 2019). To calculate biogenic habitat richness, we counted the presence of eelgrass, understory algae (brown and green), and salt marsh in each estuary (max richness = 3). Given that canopy kelps and tidal marshes are not expected to intersect the intertidal zone, they were not included as part of the biogenic habitat richness metric.

3.5. COMPARISON WITH OTHER ASSESSMENTS

In addition to the ecological metrics, we compared our clusters with metrics calculated in other studies, including cumulative impact map scores developed for the Canadian Pacific Exclusive Economic Zone (EEZ) by Agbayani and colleagues[3]. Cumulative effects assessments are a tool used around the globe to estimate the potential habitat impacts associated with multiple, often overlapping human activities (Halpern et al. 2008). The cumulative effects on a given area are determined using spatial information on the relevant habitats and activities, combined with expert guidance on the vulnerability of each habitat to the mapped activities. In the Pacific Region, cumulative effects assessments have been undertaken at coastwide (e.g., Ban et al. 2010; Clarke Murray et al. 2015) and regional (Martone et al. 2018; Boyd et al. 2022) scales and updates have recently been completed on a new coastwide assessment in support of marine spatial planning initiatives. Most recently, marine cumulative impacts have been calculated at a 1 km spatial resolution across the EEZ based on habitat-specific vulnerabilities to marine and terrestrial activities[2] (Murray et al. 2024). We averaged the cumulative impact scores overlapping each estuary and compared estuary scores to clusters in a box plot to assess the distribution of scores per cluster.

In addition, cluster results were compared to estuary rankings for waterbirds on the BC coast developed by the PBHJV (2020). The rankings were based on five biophysical variables: estuary size, species rarity, waterbird density, herring spawn, and salmon escapement. Scores for each variable were standardized, combined, and placed into five importance classes, with Class 1 being the highest scoring estuaries and Class 5 being the lowest scoring estuaries (Ryder et al. 2007; Pacific Birds Habitat Joint Venture Technical Team 2020). We compiled waterbird importance scores for each estuary and compared scores to clusters.

4. ESTUARY ASSESSMENT RESULTS

4.1. SPATIAL DATA COMPILATION

4.1.1. Summary of Marine and Terrestrial Activities

Across the 439 estuaries, all estuaries had at least one marine or terrestrial activity present (Figure 4). The list of activities for each estuary are shown in Table G1 (see data dictionary Table G4 for details on dataset names and units). There were 29 possible marine activities (median = 6, mean = 6.3), and 12 possible terrestrial activities (median = 3, mean = 3.25). There were five estuaries with only one marine activity present (proximity to shipping corridors), and these were generally located at the end of fjords on the north coast (e.g., Hastings Arm – Observatory Inlet, Kitlope Anchorage – Gardner Canal, Green Inlet). There were 84 estuaries without any terrestrial activities present (Table G1). These estuaries were dispersed across the north and central coasts and the west coast of Vancouver Island, and they generally were associated with small watershed areas further from population centers. In general, the central coast had very few terrestrial activities present except for estuaries at the end of long inlets with large watersheds that extend beyond the Coast Mountains, where activities such as logging and burned areas were more prevalent (e.g., Bella Coola watershed).

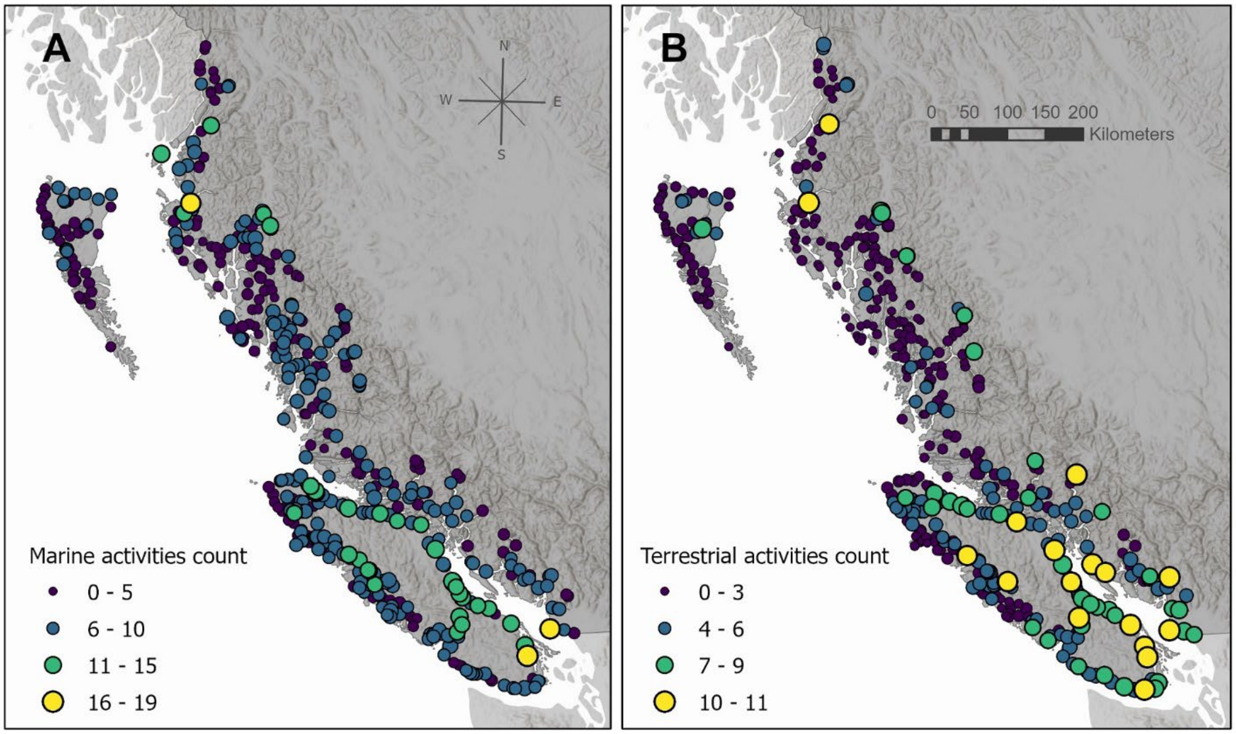

Figure 4. Count of (a) marine and (b) terrestrial human activities relevant to BC estuaries. There were 29 possible marine activities and 12 possible terrestrial activities analyzed.

No estuaries had either all of the marine or all of the terrestrial activities present (Figure 4; see Figure 5 for example of an estuary with many activities present). The areas that had the most marine activities present were estuaries in the Strait of Georgia and the Skeena River estuary near Prince Rupert. The estuary with the most marine activities (19 of 29 marine activities) was the Cowichan-Koksilah estuary, followed by the Fraser and Skeena river estuaries (17 of 29 marine activities). The areas with the most terrestrial activities (11 of 12 activities) were estuaries in the Strait of Georgia, the Skeena River estuary, and estuaries along the west coast of Vancouver Island closer to population centers (Port Alberni, Sooke) (Table G1). The areas with the most total activities (both marine and terrestrial) were in the Strait of Georgia and the Skeena River estuary, with the Cowichan River having the highest activity counts (30 activities).

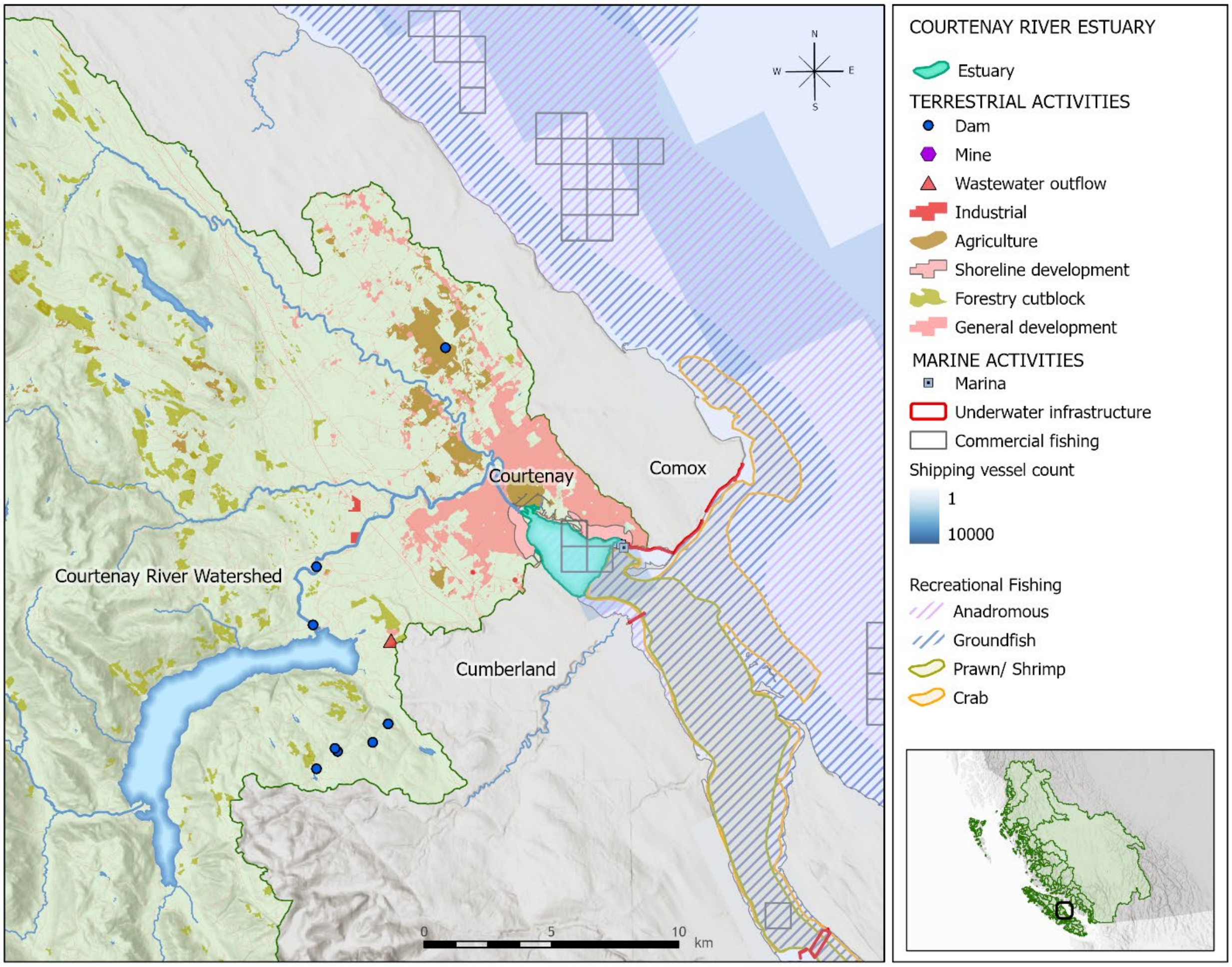

Figure 5. Map showing an example of an estuary with many activities present (Courtenay River estuary). There were 23 activities—10 marine and 13 terrestrial. The following activities were present but are not shown due to data sharing restrictions or because they are not visible at this scale: finfish aquaculture, freshwater obstructions, dredging, aquatic invasives, recreational boating, derelict vessels. The buffers for certain marine activities that represent the range of influence are not shown for visualization purposes (e.g., 2 km range of influence of marinas). Only 4th order or higher rivers are shown.

A summary of the count and percent of estuaries that overlapped each activity is shown in Table G2. The marine activities most prevalent in the estuaries were shipping and recreational boating (100% and 96%, respectively); however, the large range of influence of shipping (30 km) and the modeled grid of recreational boating with very small values resulted in a wide range of values for these activities (Table G1, Table G2). The next most frequent marine activity was commercial prawn trap fishing which occurred in or adjacent to 48% of the estuaries. The most prevalent terrestrial activities were the aggregated categories: general development in the watershed (73% of estuaries) and shoreline development (65%). Of the non-aggregated categories, forestry harvested areas were the most present in the watersheds (54%) (Table G2).

While we discuss just the occurrence of activities in this section, the results of the cluster analysis (Section 4.2) account for the relative area/intensity of each activity, and the maps for individual activities (Appendix F) are symbolized by area/intensity. In general, the area/intensity of the activities tended to be positively correlated, with the highest correlations occurring between the terrestrial activities (Figure 6).

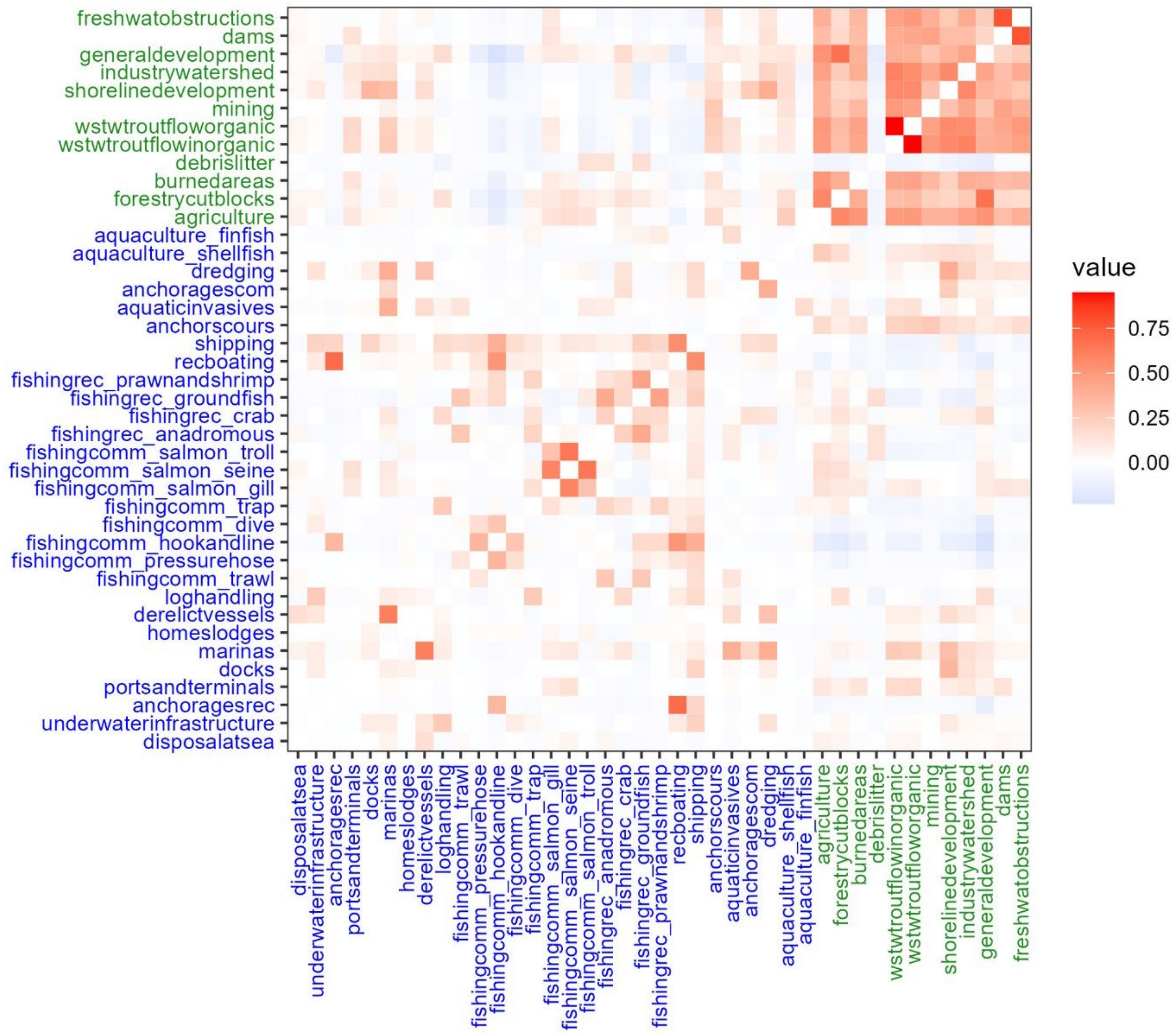

Figure 6. Pairwise correlations between the intensity/area of the human activities. Terrestrial activities are labelled in green, marine activities are labelled in blue. Each square represents a pairwise correlation between two activities with red colours indicating positive correlations and blue colours indicating negative correlations.

4.2. CLUSTER ANALYSIS

This analysis classified estuaries within Canada's Pacific Region into five categories based on the anthropogenic activities that occur within the estuaries and their watersheds. The large variation and number of anthropogenic activities that impact estuaries poses a challenge for determining which estuaries are most impacted and for identifying strategies to mitigate these impacts. Therefore, we elected to use hierarchical clustering to define characteristic types of estuaries based on these anthropogenic activities. This analysis does not provide a quantitative ranking of anthropogenic activity intensity for each estuary, but instead allowed us to identify groupings of estuaries that experience common types and intensities of anthropogenic impacts.

4.2.1. Number of Anthropogenic Activity Clusters

Our analysis found the best support for 5 clusters of estuaries across the Pacific Region based on their anthropogenic activities (Figure 7). This cluster number was selected as the best level of differentiation based on 8 of the 23 validation indices in the NbClust R package (Charrad et al. 2014). The next best number of clusters was determined to be 8, which was selected by 7 indices. All other numbers of clusters were selected by 3 or fewer indices. The PCA ordination plots illustrate the multivariate associations between the anthropogenic activities and the estuary clusters (Figure 8).

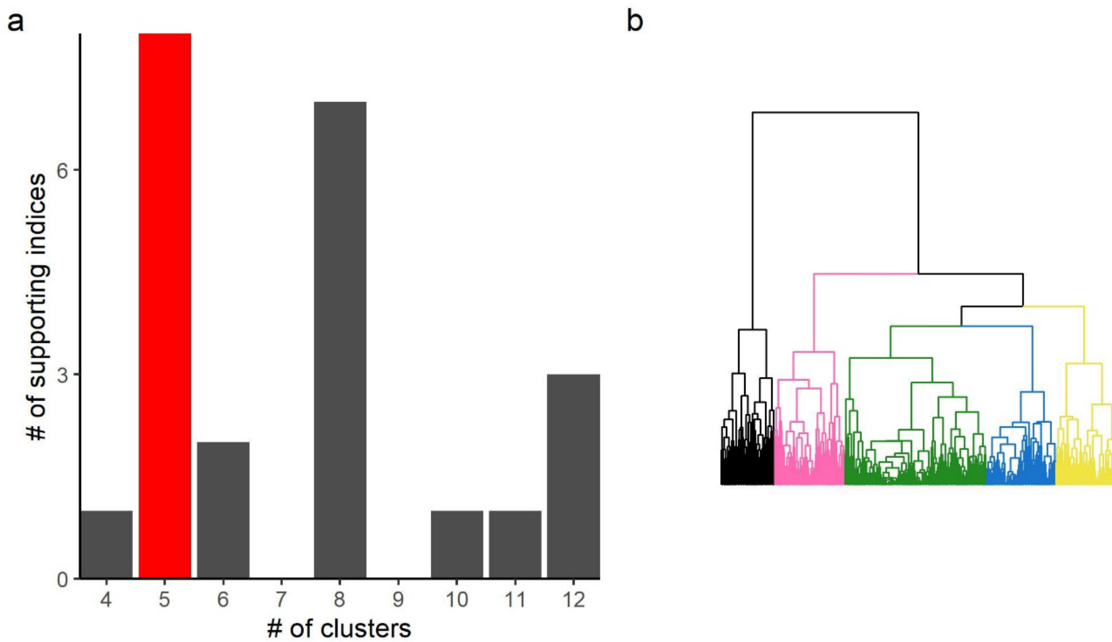

Figure 7. Number of indices supporting the selection of each number of clusters between 4 and 12 (a) with the selected number shown in red, and dendrogram based on similarity of anthropogenic activities with the branch colours showing the selected clusters (b).

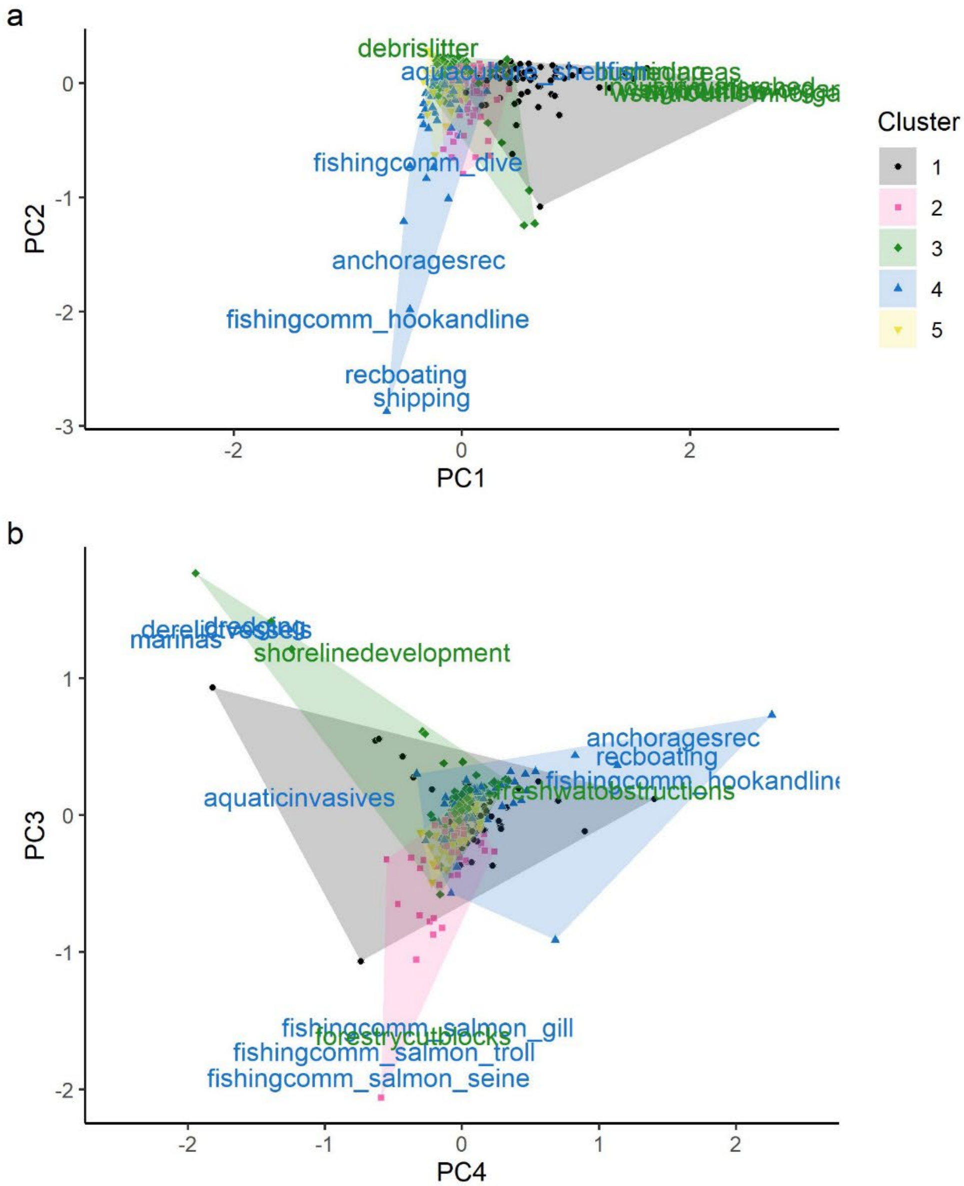

Figure 8. Principal component plots showing PCA axes 1 and 2 (a) or 3 and 4 (b). The points represent the individual estuaries, distinguished by colour and shape for each cluster, the polygons show the outer convex hull of the space covered by points in each cluster, and the center of the words indicate the loading of the individual anthropogenic activities on the PCA axes. Names for terrestrial activities are coloured green and marine activities are coloured blue. For clarity, we only show anthropogenic activities with the highest loadings (i.e., in the highest or lowest 10th percentile) on the PCA axes shown.

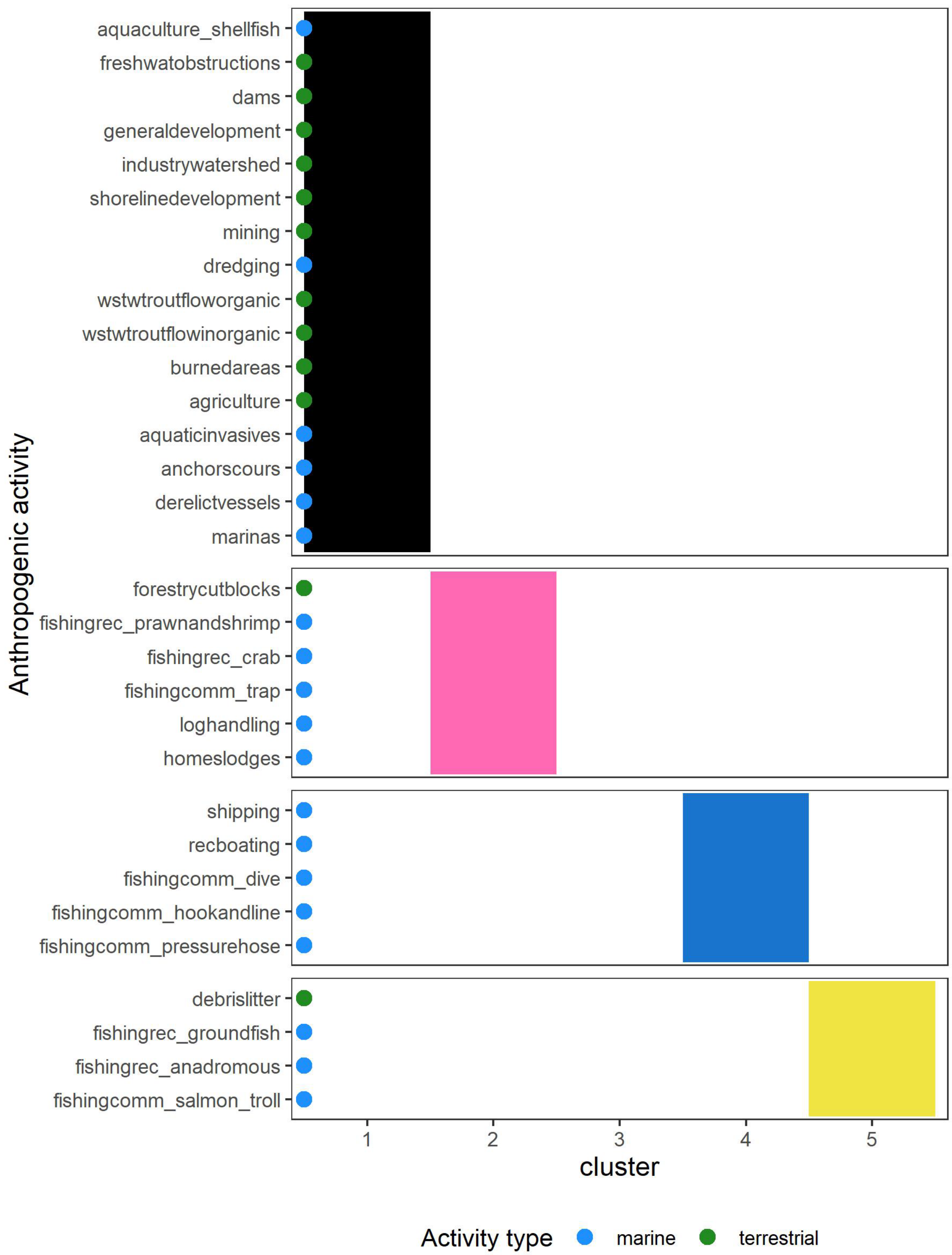

Figure 9. Anthropogenic activities that were significantly associated with each cluster (p = 0.05). Clusters are coloured using the same colour scheme in Figures 6 and 7, and activity type is colour coded by dots on the y axis. Anthropogenic activities that were not significantly associated with a cluster are not shown on this figure and no activities were significantly associated with cluster 3. The dots on the left margin indicate the type of anthropogenic activity (i.e., marine, or terrestrial). Note that activities that are significantly associated with one cluster can still occur in estuaries from other clusters.

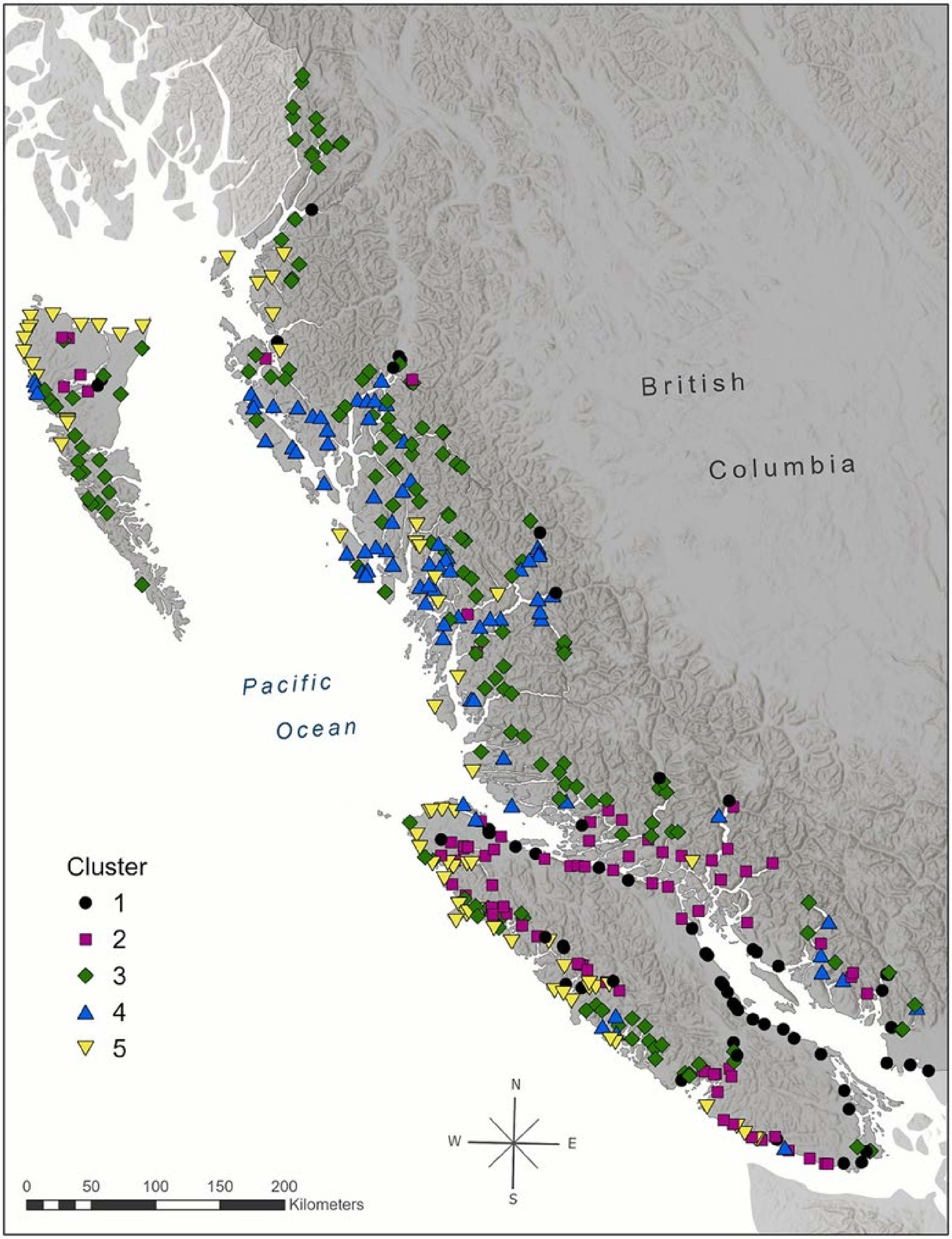

Figure 10. Map of the estuaries across the BC coast, with the point shape and colour indicating the cluster determined based on associated anthropogenic activities.

Table 3. Description of estuary categories resulting from cluster analysis of associated anthropogenic activities and stressors. Associated activities are those that have significantly (p<0.05) higher magnitude in a cluster compared to the other clusters. Note that activities that are significantly associated with one cluster can still occur in estuaries from other clusters.

Cluster # and symbol	General description	# estuaries	# significantly associated activities	# of non-zero activities (mean and range)	Associated activities	Location	Fish and fish habitat examples	Climate highlights (mean values)
1 ●	Large estuaries and watersheds with highest numbers of human activities (e.g., Fraser, Skeena, Nass)	59	16	17.5 [11–30]	shellfish aquaculture freshwater obstructions dams general development industry in watershed shoreline development mining dredging wastewater outflow (organic) wastewater outflow (inorganic) burned areas agriculture aquatic invasives anchor scours derelict vessels marinas	Mainly Strait of Georgia Bioregion; also scattered across all parts of the region.	Geometric mean salmon escapement biomass – 29,883 kg % of estuaries with two or more intertidal biogenic habitat types present: 97%	Highest air temperature (3.41°C) and stream temperature (2.53°C) change Lowest precipitation change (20.2 mm/yr.) Second lowest sea level rise (0.551 m)

Cluster # and symbol	General description	# estuaries	# significantly associated activities	# of non-zero activities (mean and range)	Associated activities	Location	Fish and fish habitat examples	Climate highlights (mean values)
2	Medium sized estuaries and watersheds with moderate levels of human activity (e.g., Sarita River, Jordan River, Mohun Creek)	78	6	11.7 [7–20]	forestry cut blocks recreational prawn and shrimp fishing recreational crab fishing commercial prawn trap fishing log handling floating homes and lodges	Mainly Vancouver Island, and mainland to the east of Vancouver Island (Northern and Southern Shelf bioregions), with a few estuaries scattered across other regions.	Geometric mean salmon escapement biomass – 5,052 kg % of estuaries with two or more intertidal biogenic habitat types present: 77%	Second highest air temperature (3.37°C) and stream temperature (2.41°C) change Second lowest precipitation change (27.2 mm/yr.) Lowest sea level rise (0.537 m)
3	Medium sized estuaries and watersheds with lower levels of human activity (e.g., Kitlope River, Deena Creek, Bear River)	157	0	7.4 [1– 5]	-	Throughout region but more common on Haida Gwaii and the central and northern coast (Northern Shelf Bioregion).	Geometric mean salmon escapement biomass – 4,396 kg % of estuaries with two or more intertidal biogenic habitat types present: 75%	Moderate air temperature (3.20°C) and stream temperature (2.37°C) change Second highest precipitation change (40.8 mm/yr.) Second highest sea level rise (0.612 m)

Cluster # and symbol	General description	# estuaries	# significantly associated activities	# of non-zero activities (mean and range)	Associated activities	Location	Fish and fish habitat examples	Climate highlights (mean values)
4	Small estuaries and watersheds with lower levels of human activity (e.g., Betterridge Inlet, Havenor Lagoon, Oyster Bay)	77	5	6.0 [1–12]	shipping recreational boating commercial dive fishing commercial hook and line fishing commercial pressure hose fishing	Mainly Central and Northern Coast (Northern Shelf Bioregion).	Geometric mean salmon escapement biomass – 86 kg % of estuaries with two or more intertidal biogenic habitat types present: 57%	Second lowest air temperature (3.02°C) and stream temperature (2.24°C) change Second highest precipitation change (40.9 mm/yr.) Moderate sea level rise (0.585 m)
5	Small estuaries and watersheds with moderate levels of human activities (e.g., San Josef River, Pachena River, Skonun River)	68	4	9.16 [4–15]	debris and litter recreational groundfish fishing recreational salmon fishing commercial salmon trolling	Mainly exposed estuaries on the west and north sides of Vancouver Island and Haida Gwaii but also some scattered across the central and northern coast (Northern and Southern Shelf bioregions).	Geometric mean salmon escapement biomass – 148 kg % of estuaries with two or more intertidal biogenic habitat types present: 75%	Lowest air temperature (2.91°C) and stream temperature (1.93°C) change Highest precipitation change (41.1 mm/yr.) Highest sea level rise (0.614 m)

4.2.2. Characterizing the Clusters

The analysis identified five clusters that span a gradient from low to high numbers of anthropogenic activities (Figure 9, 10, Table 3). The primary distinction in the hierarchical clustering is between cluster 1 and the other four clusters. Cluster 1 estuaries generally have the highest numbers of activities, particularly terrestrial activities. The other four estuary clusters generally have fewer activities, and the activities that are present are mostly associated with the marine environment and forestry. Of those four clusters, there are two that have intermediate numbers of activities and two that have low numbers of activities (Table 3). The multivariate relationship between the activities and the clusters is shown in the PCA in Figure 8.

4.2.2.1. High activity cluster

The high development cluster (cluster 1; black circles) is characterized by estuaries with high numbers of human activities (mean = 17.5) that are associated with terrestrial development and populated areas (Table 3, Figure 10). These estuaries tend to be large and are associated with larger rivers and watersheds (Table 3), including the Fraser, the Skeena, and the Nass. Estuaries in this cluster are mostly located in the Strait of Georgia, but also occur in all other regions of the province (Figure 10).

4.2.2.2. Intermediate activity clusters

The two clusters with intermediate numbers of activities are clusters 2 (pink squares) and 5 (yellow triangles). Cluster 2 estuaries are mostly located on Vancouver Island, or on the mainland to the east of Vancouver Island, although not around the Strait of Georgia (Figure 10). There are also some estuaries in this cluster in sheltered areas of Haida Gwaii and a couple of estuaries on the central and northern coast. Estuaries in cluster 2 have an average of 11.7 activities (Table 3) and six activities are significantly associated with the cluster: forestry cut blocks, log handling, floating lodges and homes, as well as recreational crab fishing and commercial prawn trap fishing (Figure 9). Cluster 5 estuaries tend to be located on the outer coast of Vancouver Island and Haida Gwaii, and to a lesser extent on outer areas of the central and northern coast (Figure 10). Estuaries in cluster 5 have an average of 9.16 activities (Table 3) and four activities are significantly associated with the cluster: debris and litter, recreational groundfish fishing, recreational anadromous fishing, and commercial salmon trolling (Figure 9).

4.2.2.3. Low activity clusters

The two clusters with low numbers of activities are cluster 4 (blue triangles) and cluster 3 (green diamonds). Cluster 4 estuaries occur mainly in the central and northern coast (Figure 10). Estuaries in cluster 4 have an average of six activities (Table 3) and five activities are significantly associated with the cluster: shipping, recreational boating, commercial dive fishing, commercial hook and line fishing, and commercial pressure hose fishing (Figure 9). Cluster 3 estuaries occur throughout the region but are more common on Haida Gwaii and on the central and northern coast (Figure 10). Estuaries in cluster 3 have an average of 7.5 activities (Table 3) but the identity of these activities is variable from estuary to estuary, so no activities are significantly associated with this cluster (Figure 9).

4.2.2.4. Activities not associated with any cluster

Ten activities are not significantly associated with any individual cluster (Figure F9, F10). These are commercial anchorages, recreational anchorages, finfish aquaculture, disposal at sea, docks, commercial gillnet salmon fishing, commercial seine salmon fishing, commercial trawl fishing, ports and terminals, and underwater infrastructure.

4.2.3. Summary of Climate Change Stressors

Every estuary is expected to experience some degree of climate change based on the compiled spatial data for air temperature change, stream temperature change, precipitation change, and sea level rise (Figure 11, Figure 12). Predicted air temperature change was highest for estuaries located up long inlets on the mainland of BC (e.g., Bute Inlet, Knight Inlet, Portland Canal), and lowest for those more northerly and exposed estuaries (e.g., Haida Gwaii) (Figure 11a). Predicted stream temperature change followed similar spatial patterns as air temperature change, with the largest increases located at estuaries up long inlets (e.g., Bute Inlet, Dean Channel, Burke Channel) (Figure 11b). Precipitation change was greatest for estuaries along the outer coast of Haida Gwaii and the north coast. The northwest coast of Vancouver Island will also experience increases in precipitation relative to the rest of the island. The south coast of BC is projected to experience little change in precipitation (Figure 11c). Lastly, all estuaries will experience at least 0.35 m of sea level rise, with sea level rise in some areas as high as 0.85 m by 2099. The most prominent areas were along the coast of Haida Gwaii and around the low-lying areas of the south coast near the Fraser River. Estuaries in Johnstone Strait will experience the least amount of sea level rise (Figure 11d).

Examining the climate variables in comparison to the counts of terrestrial and marine activities can allow us to see which estuaries may experience the highest cumulative effects (Figure 12). Estuaries in cluster 1 had the most activities present and will also experience mid to high air temperature changes (Figure 12a). A few estuaries in clusters 1, 2, 3 and 4 will experience mid to high levels of stream temperature change, but only estuaries in cluster 1 and 2 have high activity counts (Figure 12b). The most precipitation change will occur in estuaries with relatively low activity counts (Figure 12c). Estuaries across all clusters will experience high sea level rise, but only a few of these in cluster 1 also have high activity counts (Figure 12d).

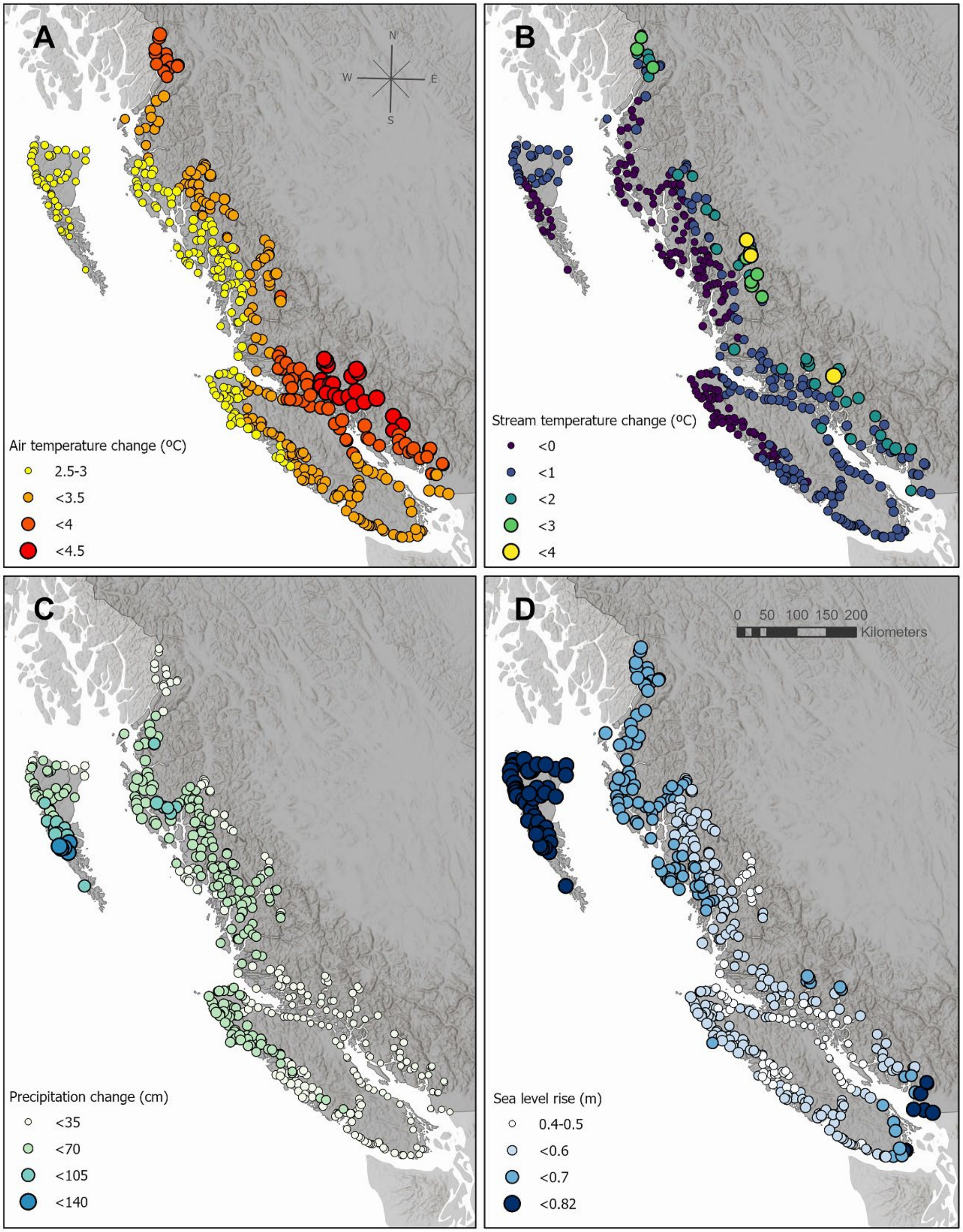

Figure 11. Climate change stressor values: (a) air temperature change, (b) stream temperature change, (c) precipitation change, (d) and sea level rise. Future temperature and precipitation projections are based on the RCP 4.5 scenario, and sea level rise is based on the RCP 8.5 scenario. Each stressor value is calculated as the change between recent conditions to end-of-century predictions (Table 1).

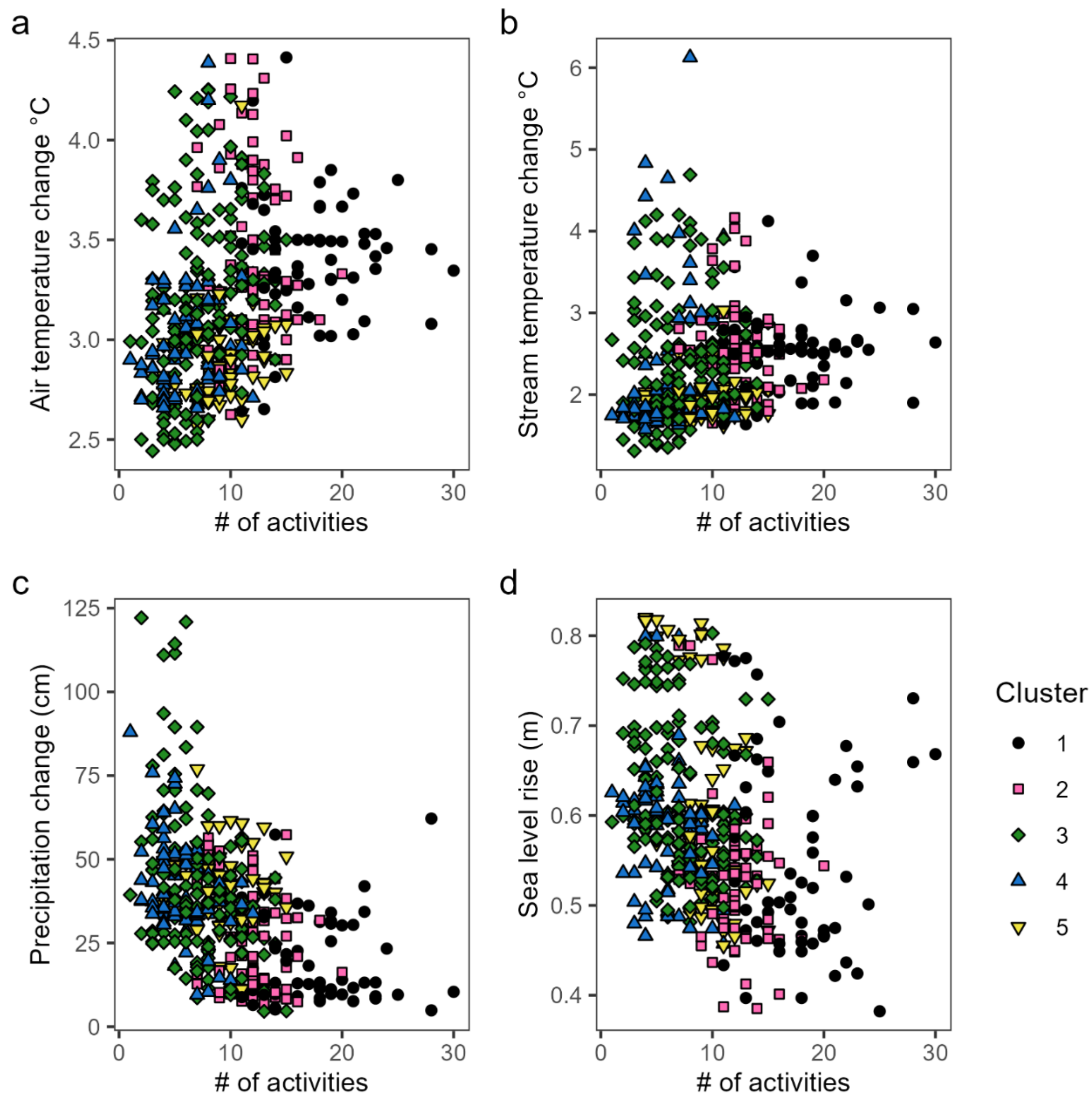

Figure 12. Scatterplots comparing the count of activities occurring in estuaries with the climate change variables per estuary by cluster: (a) air temperature change, (b) stream temperature change, (c) precipitation change, (d) sea level rise cluster.

4.3. FISH AND FISH HABITAT EVALUATION

4.3.1. Salmon

4.3.1.1. Salmon escapement: biomass and richness

The highest Pacific salmon escapement biomass values were seen for the Fraser River, Skeena/Esctall/McNeill River complex, Bella Coola/Necleetsconnay River complex, Somass River, and Kitimat River estuaries (Figure H1, Table G3; see data dictionary Table G4 for details on units). These estuaries all fell within cluster 1 and had a high number of marine and terrestrial activities (16–28 total). However, smaller estuaries such as the Nitinat River (cluster 2) estuary also supported high levels of salmon escapement biomass. The top 10% of estuaries, based on biomass, had a median size of 1.4 km^2. The highest Pacific salmon richness value of 6 was found for 180 (41%) estuaries (Table G3, Figure H1). Within each cluster, all levels of richness were present except for in clusters 1 and 4, which did not have any estuaries with a species richness of 0 (Figure 13).

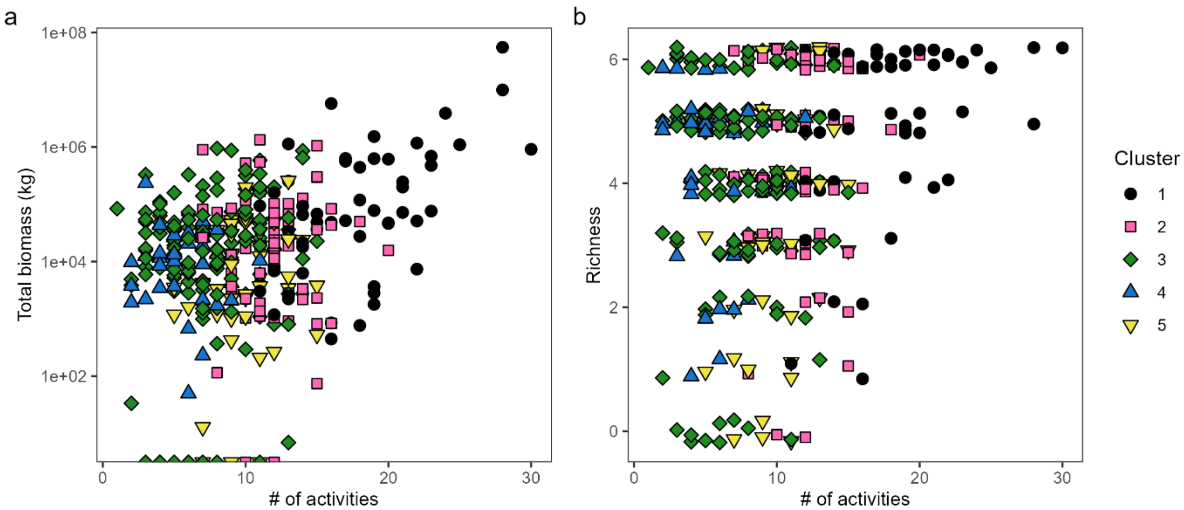

Figure 13. Scatterplot comparing the number of activities that occur within each estuary with (a) total escapement biomass and (b) richness of Pacific salmon (all species, Pink Salmon odd and even years considered separately). The colour and shape of each point indicates the estuary cluster based on associated anthropogenic activities. The y-axis is log transformed to reduce the emphasis on the few estuaries with extremely high escapement biomass. Estuaries with 0 recorded escapement biomass are shown at the lower margin of the y-axis. Richness points have been jittered for visualization purposes.

4.3.1.2. Salmon Conservation Units

All estuaries had at least one conservation unit present within their watershed. CU status had been assessed for 62 of the 254 CUs available for Chinook, Chum, Coho, Pink (even- and odd-year), and river-type Sockeye Salmon in BC, though 17 were considered data-deficient and a status has not yet been assigned. The highest counts of salmon CUs were found for the Fraser River, Skeena/Ecstall/McNeill River complex, and Nass/Ksi'Hlginx/Burton/Iknouck/Chambers/Kincolith River estuaries, which fell within cluster 1 and had many activities (12–28) (Figure 14a). Within the Fraser watershed, 27% of CUs had not been assessed and 16% had a 'Red' status (the dominant status aside from CUs that were data-deficient or not assessed). Within the Skeena watershed, 68% of the CUs that overlap the Skeena watershed had not been assessed and 3% had a 'Red' status. The majority of CUs with 'Red' ratings were associated with estuaries in cluster 1, although estuaries in cluster 2 were also associated with high numbers of CUs with 'Red' ratings (Figure 14b).

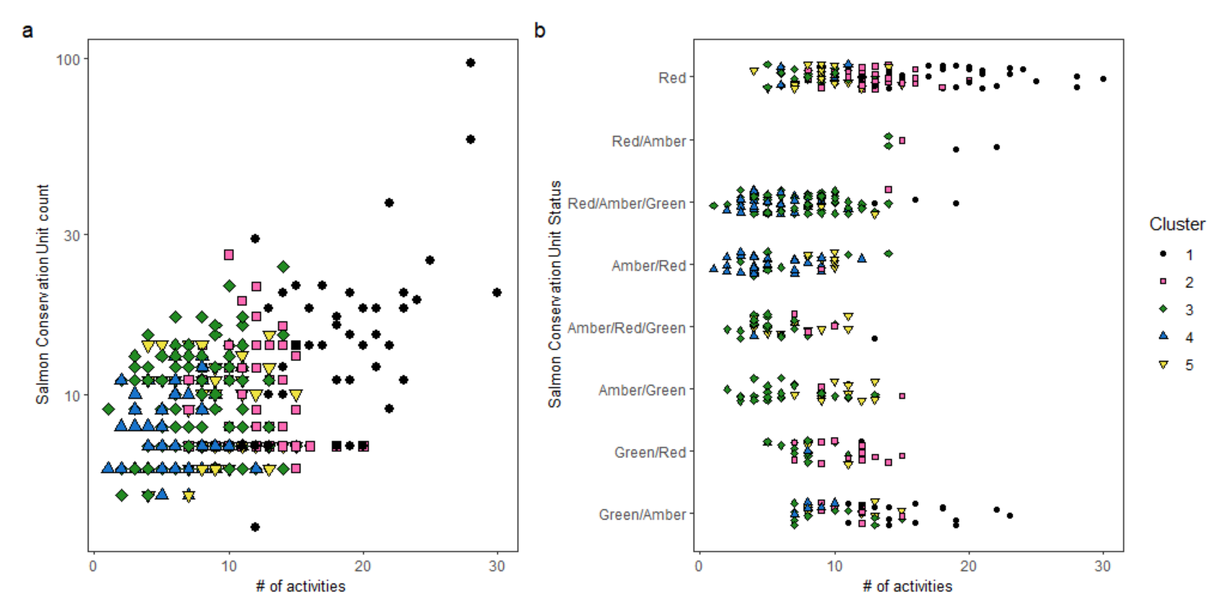

Figure 14. Scatterplot comparing the number of activities that occur within each estuary with (a) the count of Pacific salmon conservation units (CU) in the upstream watershed of each estuary and (b) because all estuaries have multiple CUs, the CU with the poorest status overlapping the associated watershed is shown. The y-axis has been log transformed in (a).

4.3.2. Forage Fish

The majority of estuaries (80%) did not have any Pacific Herring spawn biomass present (Figure H1). The highest herring spawn mean biomass values were seen for Hart Creek (cluster 1), and Toquart River, Lucky Creek and Bazett Island Area (cluster 3) (Table G3). These estuaries are off Vancouver Island and have an intermediate number of activities present (8–16).

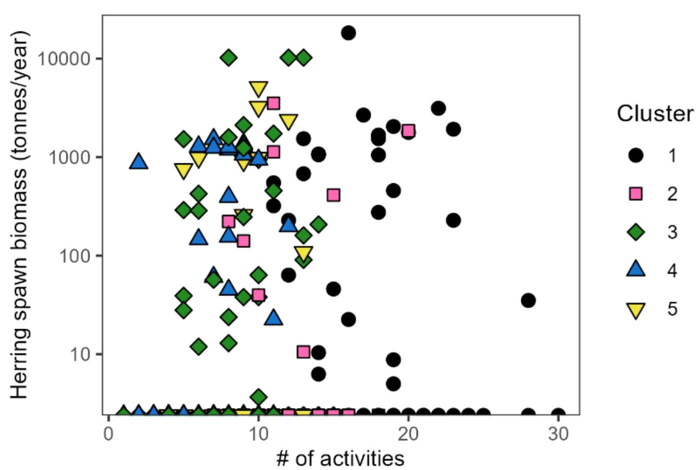

Figure 15. Scatterplot comparing the number of activities that occur within each estuary with herring spawn biomass. The y-axis has been log transformed.

Pacific Sand Lance habitat suitability scores were only available for estuaries in the Strait of Georgia. Despite that limitation, a visual assessment of cluster differences show a higher range of suitability scores in cluster 1 (black) compared to other clusters for both the Robinson et al.

(2021) model (Figure 16a) and Huard et al. (2022) model (Figure 16b). Six of the top ten estuaries for Pacific Sand Lance habitat suitability were clustered between Courtenay and Deep Bay along the east coast of Vancouver Island (Table G3; Figure H1).

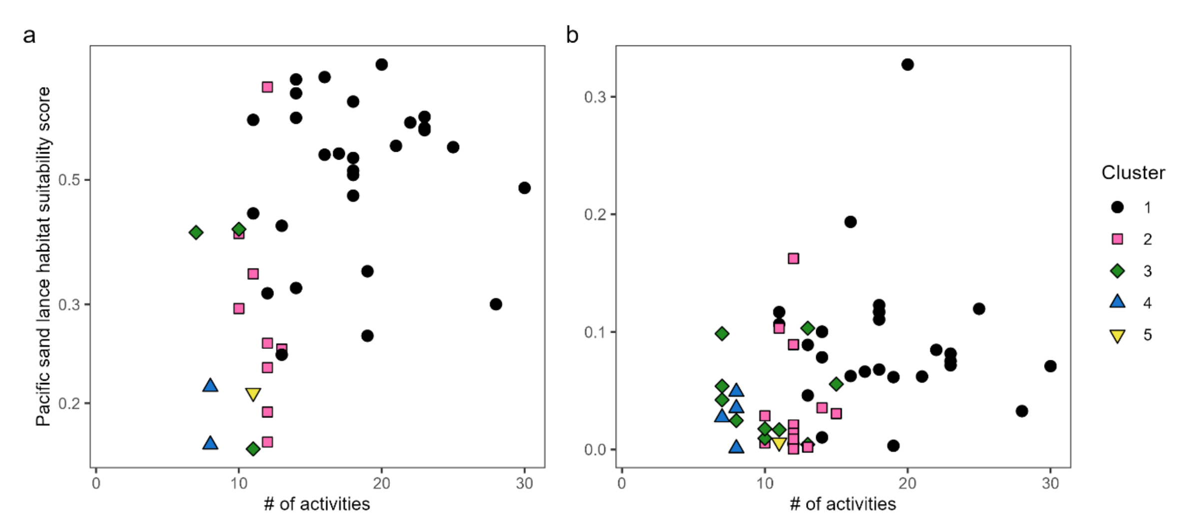

Figure 16. Pacific Sand Lance habitat suitability scores for estuaries in the Strait of Georgia. Data in (a) are from Robinson et al. (2021) and data in (b) are from Huard et al. (2022). Both studies only modeled habitat suitability in the Strait of Georgia.

Areas important for Eulachon were identified as the estuaries downstream of waterways known to be important for spawning and rearing. Overlap with Eulachon Important Areas were found for 81 (18%) estuaries (Table G3; Figure H1). Eulachon was present in estuaries for all clusters, although there was only one estuary with Eulachon in cluster 5 (Figure 17). Cluster 3 had the highest percentage of estuaries with Eulachon present (11% of estuaries). Overlap with Eulachon Important Areas were found for 81 (18%) estuaries (Table G3).

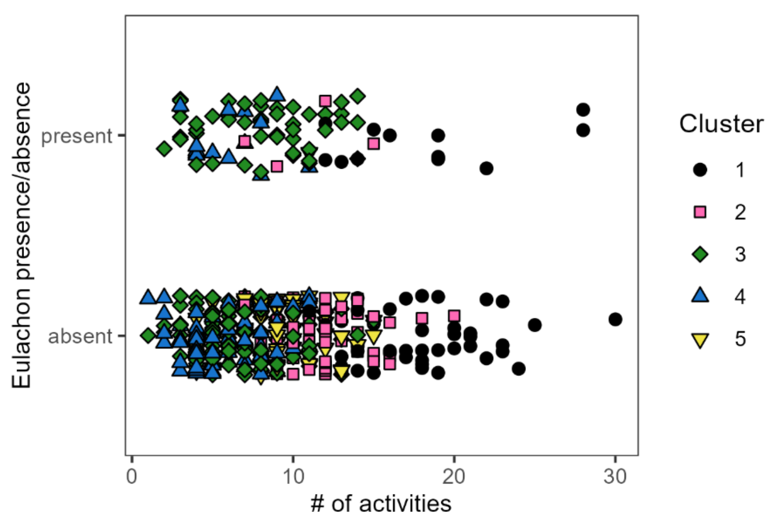

Figure 17. The presence/absence of Eulachon Important Areas in estuaries compared to activity count. Points are jittered for visualization purposes.

4.3.3. Invertebrates

Probability estimates for Dungeness Crab presence overlapped with 85% of the estuaries and was present across all clusters (Figure H1, Figure 18). Of the estuaries with values, 84% had a probability of 50% or greater, and 28% had a probability of 90% or greater and were distributed along the entire coast (Figure H1).

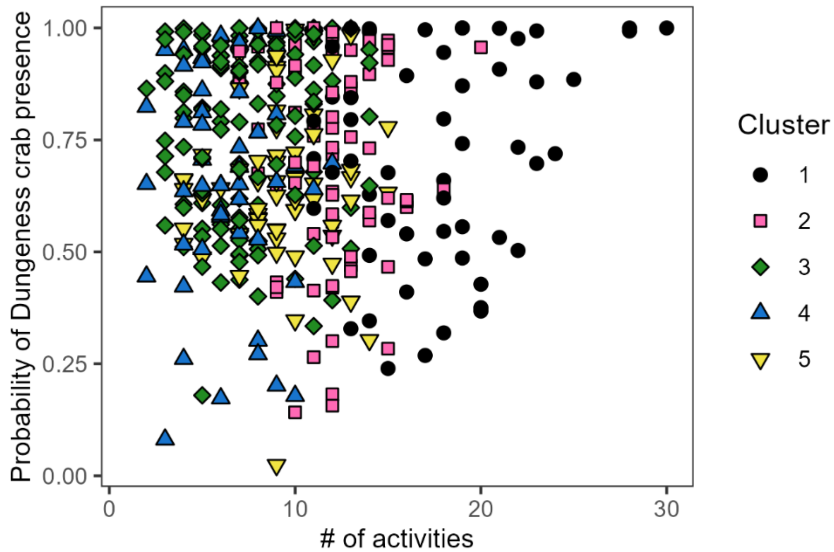

Figure 18. Scatterplot comparing the number of activities that occur within each estuary to the probability of Dungeness Crab presence.

Of the 439 estuaries, 238 overlapped with shellfish research surveys and commercial catch observations. Spot Prawn was found in 226 of these estuaries (Table G3; Figure H1). Spot Prawn has been observed in estuaries for all clusters (Figure 19). Cluster 3 had the highest percentage of estuaries with Spot Prawn present (20% of estuaries).

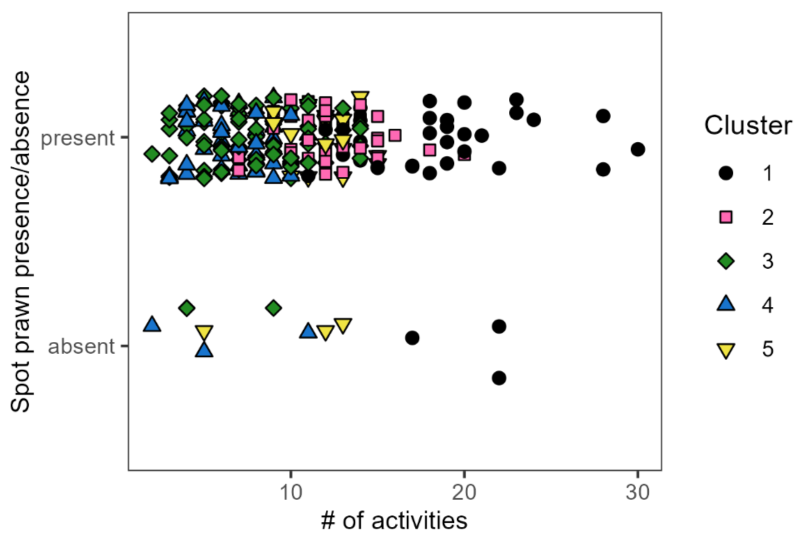

Figure 19. Scatterplot comparing the number of activities that occur within each estuary to Spot Prawn presence/absence. Only estuaries with observations are shown. Points are jittered for visualization purposes.

4.3.4. Estuarine Habitats

4.3.4.1. Eelgrass

Fifty-seven percent of the estuaries did not overlap with eelgrass biobands or polygons. However, we expect that there are data gaps in both eelgrass datasets (see Section 5.4.3). Where estuaries overlapped eelgrass polygons, the proportion of overlapping area varied from $<10^{-5}$ to 1, with the majority of values greater than 0.01 (Figure 20b). For the individual estuaries, the highest values for the eelgrass biobands were observed for the Banks Lakes, Megin River, and Quigley Creek (cluster 4) (Table G3). For the eelgrass polygon data, the highest overlaps were seen for the Waukwaas Creek (cluster 1), Kwatleo Creek, Naden River/Davidson Creek complex (cluster 3), and Yakoun River (cluster 1) (Table G3; Figure H2).

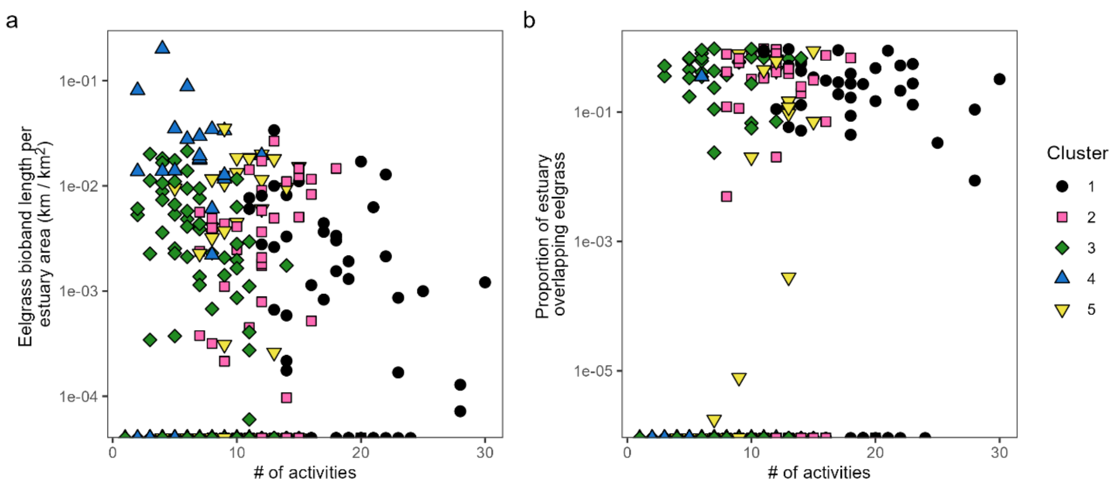

Figure 20. Scatterplot comparing the count of activities in estuaries with the amount of eelgrass in estuaries: (a) the length of linear eelgrass Shorezone bioband units per estuary area, and (b) eelgrass meadow polygons overlapping with estuaries. The y-axes are log transformed; however, the axis limits differ between each plot for visualization purposes.

4.3.4.2. Macroalgae

Seventy-nine percent of the estuaries did not overlap with macroalgae biobands or polygons. However, we expect data gaps in both of these datasets and with the bioband data for the understory kelp and green macroalgae biobands (see Section 5.4.3). Where estuaries overlapped brown canopy kelp polygons, the proportion of overlapping area varied from <0.01 to 1 (Figure 21b). For the individual estuaries, the highest overlaps with the canopy kelp biobands were seen in the Shade Island area, Keecha Creek, and Lombard Point (cluster 4) (Table G3, Figure H2). The highest overlaps with the canopy kelp polygons were found for the Keogh River (cluster 2), Nahwitti River (cluster 5), and Somass River (cluster 1) estuaries (Table G3, Figure H2).

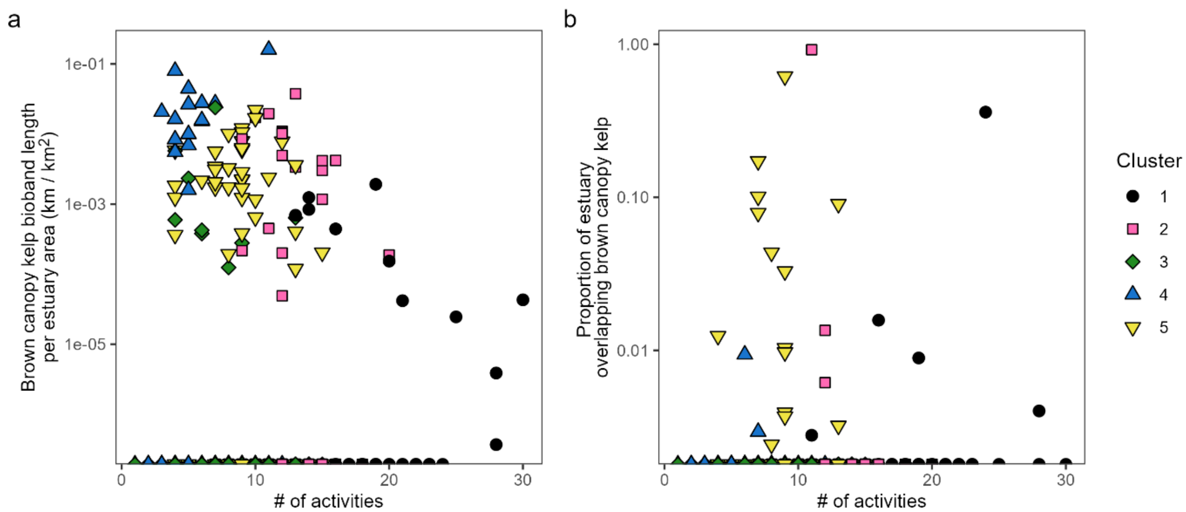

Figure 21. Scatterplot comparing the count of activities occurring in estuaries with brown canopy kelp (Bull Kelp and Giant Kelp): (a) the length of linear Shorezone bioband units per estuary area, and (b) brown canopy kelp polygons overlapping with estuaries. The y-axes are log transformed; however, the axis limits differ between each plot for visualization purposes.

There were 31% of the estuaries that overlapped with brown understory kelp biobands (Figure 22). For the individual estuaries, the highest overlap proportions with the understory brown kelp bioband were found for the Shade Island Area, Keecha Creek, Unnamed_268, Hankin Point, and Lombard Point estuaries (Table G3; Figure H2), all of which fell within cluster 4 based on anthropogenic activities.

There were 74% of the estuaries that overlapped with green macroalgae biobands. For the individual estuaries, the highest overlap proportions with the green macroalgae bioband were seen at Ellerslie Lagoon, Banks Lakes, Quigley Creek, Keecha Creek, and Waterfall Inlet estuaries (Table G3; Figure H2), all of which fell within cluster 4 based on anthropogenic activities.

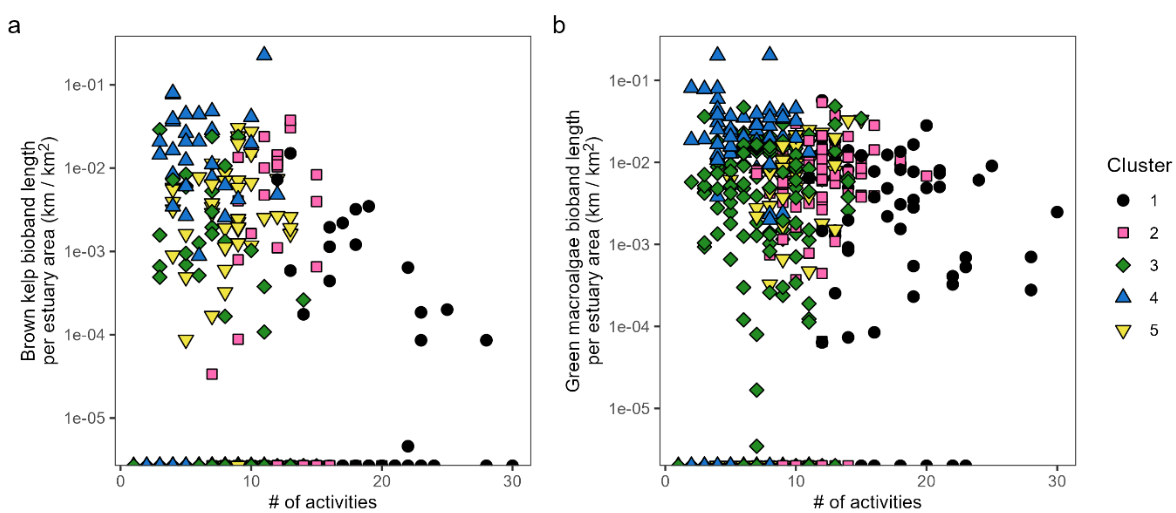

Figure 22. Scatterplot comparing the count of activities occurring in estuaries with understory (a) brown and (b) green macroalgae biobands, measured as the length of linear Shorezone units per estuary area.

4.3.4.3. Salt marsh

There were 81% of the estuaries that overlapped with salt marsh biobands (Figure 23). For the individual estuaries, the highest overlap proportions were seen at the Kumowdah River (cluster 4), Ellerslie Lagoon (cluster 4), Stawamus River (cluster 1), Kumdis Slough (cluster 3), and Quigley Creek (cluster 4) estuaries (Table G3, Figure H2).

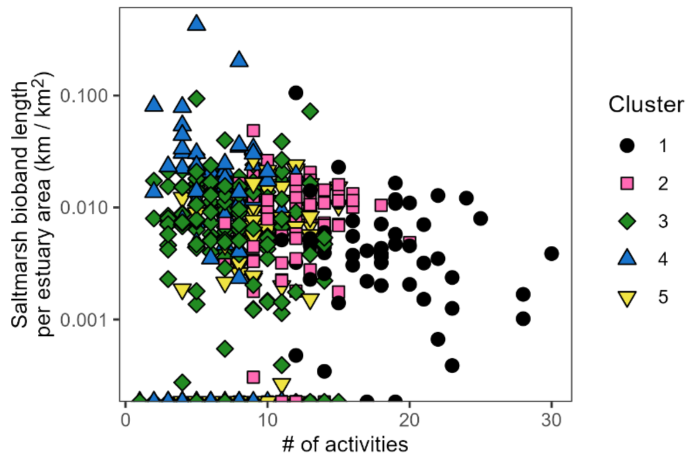

Figure 23. Scatterplot comparing the count of activities occurring in estuaries with saltmarsh biobands, measured as the length of linear Shorezone units per estuary area.

Shorezone bioband data for tidal marsh were found for the following estuaries: Cowichan River, Goldstream River, Gordon River, Pachena River, San Juan River, Sarita River, and Skeena River estuaries. Given its limited spatial overlap with the estuaries included in this study, tidal marsh information from the Shorezone database were not assessed further.

4.3.4.4. Substrate type

There were 27% of estuaries that had all substrate types present and 11% that were comprised of only one type of substrate (Figure 24). Rock was the most frequent substrate type present (91% of estuaries); however, mud was the dominant substrate type by proportion of area (average of 51% of estuary area vs. 31% rock) (Table G3, Figure H3). There were no clear differences in substrate composition among clusters or by activity count.

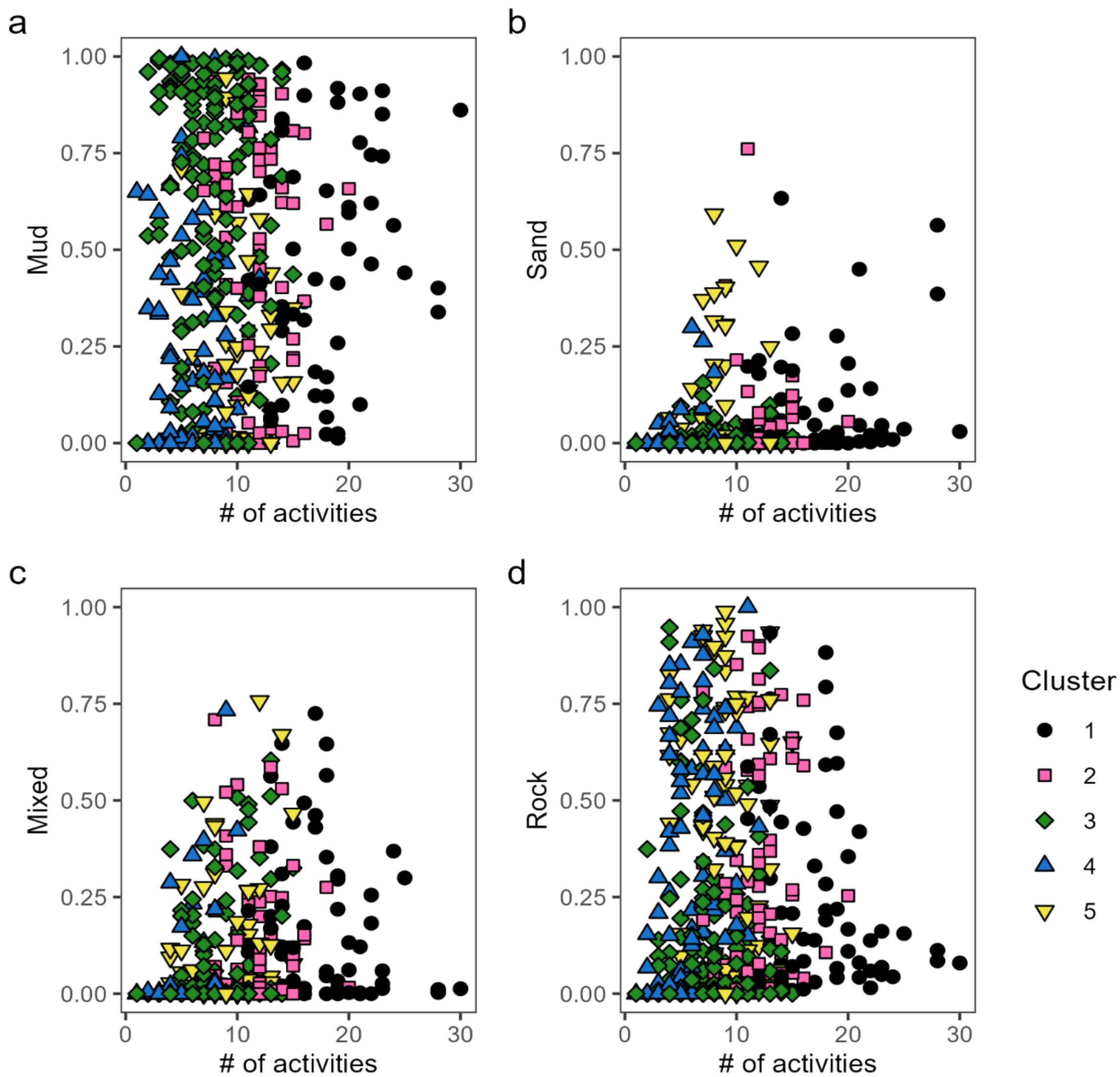

Figure 24. Scatterplots comparing the count of activities occurring in estuaries with the proportion of estuary area comprised of each substrate type: (a) mud, (b) sand, (c) mixed, (d) rock by cluster.

4.3.4.5. Rugosity

There was minimal variation in rugosity among most estuaries (Figure 25). Swallop Creek, Holti Point, and "Unnamed 318" estuary in cluster 4, as well as Georgie River estuary in cluster 3 had the greatest values of rugosity (Table G3; Figure H3). These estuaries had low number of activities present (4–5).

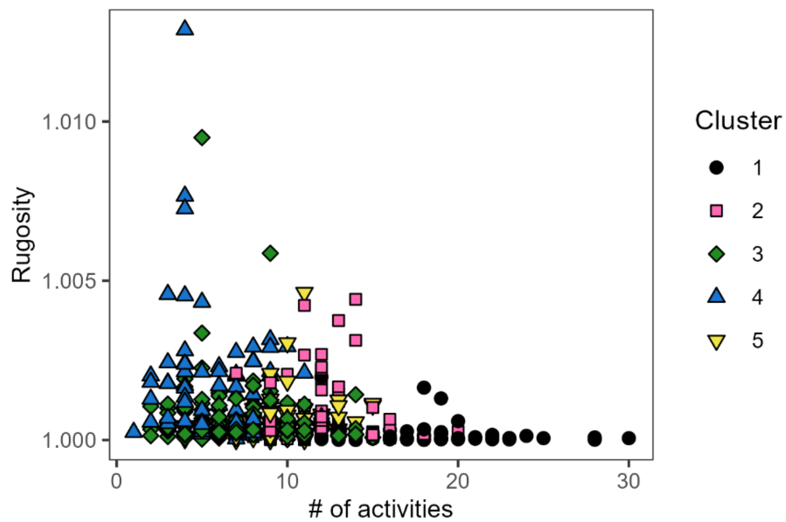

Figure 25. Scatterplot comparing the count of activities occurring in estuaries with averaged rugosity values per estuary.

4.3.4.6. Biogenic habitat richness

All three intertidal biogenic habitat types considered (eelgrass, saltmarsh, macroalgae) were present in 36% of the estuaries (Figure 26). There were 5% of the estuaries without any biogenic habitat; however, as noted there are likely gaps in the bioband and polygon datasets. Generally, estuaries with lower habitat richness also had fewer activities present but estuaries with high richness had a wide range of activities present.

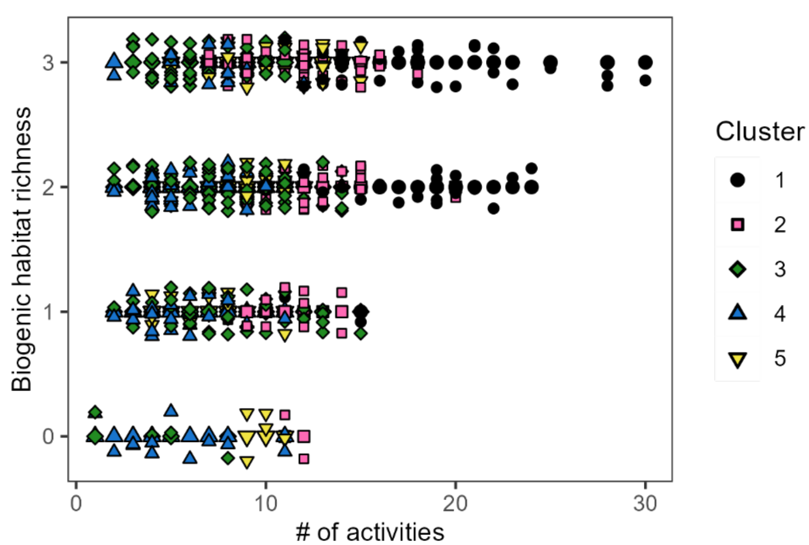

Figure 26. Scatterplot comparing the count of activities occurring in estuaries with biogenic habitat richness. Biogenic habitat types include eelgrass, saltmarsh, and understory algae (brown kelp and green macroalgae combined).

4.4. COMPARISONS

4.4.1. Cumulative Impact Mapping

Generally, the cumulative impact score of an estuary was positively correlated with the number of activities (Figure 27). Estuaries in cluster 1 had the highest scores and number of activities, and estuaries in clusters 2 and 4 also had high scores but fewer activities. The Glenlion River estuary in cluster 1 had the highest impact score overall, with 18 activities present. Shade Island estuary in cluster 4 and Youghpan Creek estuary in cluster 2 had the next highest scores but with only 11 and 10 activities, respectively.

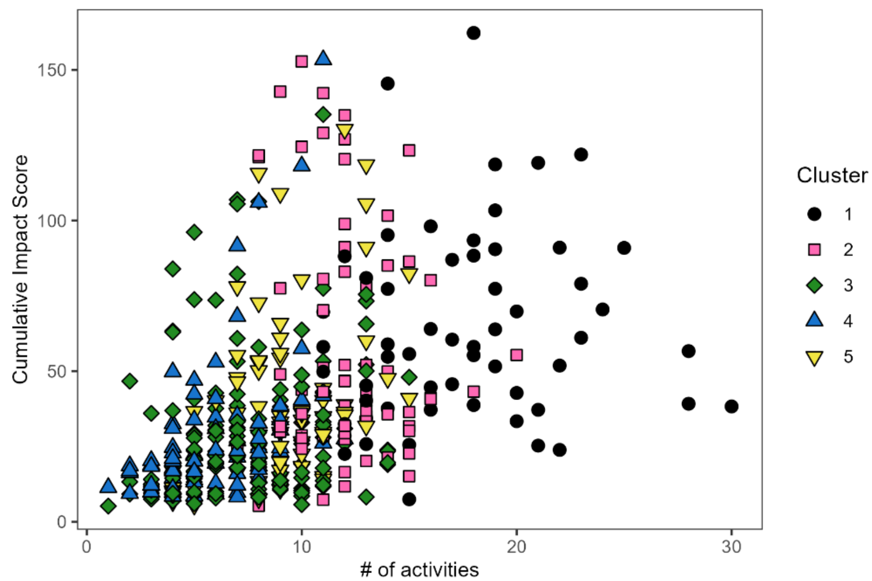

Figure 27. Scatterplot comparing the count of activities occurring in estuaries with cumulative impact mapping scores[3].

4.4.2. Estuary Rankings for Waterbirds

Of the 439 estuaries, 13 were ranked as most important (i.e., score of 1) for waterbirds by the Pacific Birds Habitat Joint Venture Technical Team (2020). These were primarily estuaries in cluster 1 (e.g., Fraser River, Cowichan River) with high activity counts as well as estuaries in cluster 3 (e.g., Toquart River, Cypre River) with lower to intermediate activity counts (Table G3; Figure H4). There were no clear differences among clusters except that cluster 1 generally had estuaries ranked as more important (Figure 28). Three of the estuaries of highest importance for waterbirds were also ranked high based on salmon escapement biomass, all from cluster 1 with high numbers of activities: Fraser estuary (28 activities), Skeena estuary (28 activities), and Kitimat estuary (19 activities).

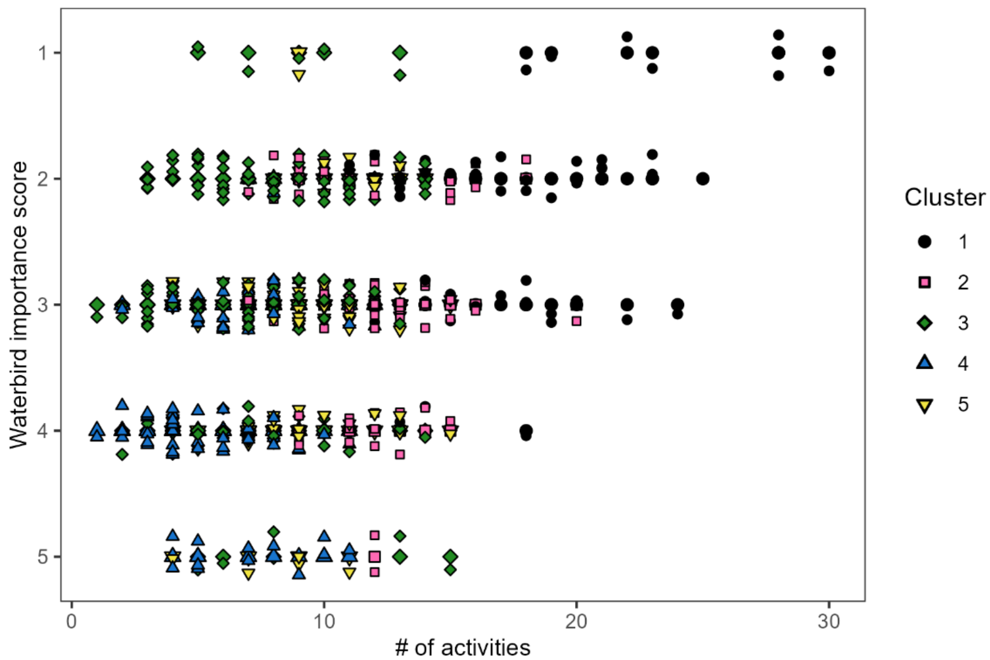

Figure 28. Scatterplot comparing the count of activities occurring in estuaries with estuary rankings for waterbirds (Pacific Birds Habitat Joint Venture Technical Team 2020) by cluster. Estuary importance for waterbirds were ranked from 1–5, with 1 being the most important and 5 being the least important.

5. DISCUSSION

5.1. BROAD-SCALE CONTEXT

It is widely acknowledged that more integrated, ecosystem-based approaches are required to protect ecosystems (Halpern et al. 2008; Pacific North Coast Integrated Management Area (PNCIMA) Initiative 2017). This includes the management of estuaries (DFO 2002; Sheaves et al. 2015; Clark et al. 2016). In this study, BC's estuaries were classified based on assessment and evaluation of anthropogenic activities, activity counts, and fish and fish habitat to provide a starting point for prioritizing estuaries for management and conservation planning. The analysis incorporated the results of a literature review for activities and associated stressors relevant to estuarine habitats, including those identified previously for juvenile salmon (Hodgson et al. 2020). To ensure relevance with ongoing MSP initiatives in the Pacific Region, the classification also utilized spatial datasets compiled in support of cumulative effects assessments and MPA network planning. The evaluations of fish and fish habitat within the estuaries can help guide where further data collection and local scale assessments would be valuable and where there may be opportunities for collaboration and important lessons for further site-specific management and conservation activities. The results can also be extended to consider impacts through ongoing cumulative effects assessments.

Knowledge of activity locations, associated stressors, and potential impacts to estuarine habitats can help identify estuaries that face similar concerns, potential mitigation options, and the partners and stakeholders with the relevant management jurisdiction. The results of this study grouped estuaries based on associated activities and considered activity type, level of use, and activity origin (i.e., terrestrial, marine). As such, the outputs also highlight potential efficiencies in management responses across multiple estuaries. For example, the activities associated with the estuaries within cluster 2 (medium sized estuaries and watersheds with moderate levels of human activity) include those related to forestry operations in the watersheds and log handling in the estuaries. The cluster 2 estuaries were also associated with recreational and commercial shellfish fisheries. Woody debris from log handling and storage operations can reduce benthic diversity and the abundance of ecologically significant species such as commercially and recreationally important Dungeness Crab (Picard et al. 2003), which could have corresponding impacts on fisheries activities. As such, collaboration among provincial, federal, and First Nations organizations involved in regulating forestry, marine tenures, and fisheries may be important.

Identifying the activities that co-occur within estuaries can also further research into how associated stressors vary within estuaries and in relation to each other. For example, the intensity and frequency of hypoxic conditions due to anthropogenic nutrient loading has been shown to vary spatially throughout an estuary and be compounded both by structures that inhibit water flow and impacts of climate change (Hughes et al. 2015). While hypoxia and associated harmful algal blooms were not stressors identified in the literature review, estuaries in cluster 1 (large estuaries and watersheds with high numbers of human activities) were associated with multiple related activities, including those that could contribute to nutrient loading or pollutants (e.g., agriculture) as well as freshwater obstructions, dams, and shoreline development that can alter freshwater outflow into the estuaries, which have shown to be related to eutrophication in estuaries (Greene et al. 2015). The cluster 1 estuaries also had the highest projected stream temperatures, another factor that, along with drought-reduced stream flows, can potentially contribute to hypoxic conditions in the future. Additional information on estuarine circulation and the inflow of fresh and oceanic waters under current and projected climate change scenarios would help elucidate the potential for hypoxia-associated impacts on estuarine species and activities such as shellfish aquaculture, an activity associated with cluster 1 estuaries.

The outputs of the cluster analyses also help to better characterize how estuaries along the BC coast meet the EBSA criteria. Estuaries within clusters 3 (medium sized estuaries and watersheds) and 4 (small estuaries and watersheds) faced lower levels of activities, with means of 7.4 and 6.0 activities, respectively (Table 3). These estuaries may score higher for the naturalness criterion that has not been previously assessed for individual estuaries (Rubidge et al. 2020). Fifty-three percent of estuaries along the coast were in clusters 3 and 4 and more than one-third of estuaries, primarily located on the North and Central coasts and Haida Gwaii, were classified into cluster 3. The cluster 3 estuaries had the second highest projected changes in precipitation and sea level rise, and moderate changes anticipated for air and stream temperatures associated with climate change. Research into MPAs suggests that areas with lower levels of anthropogenic activities and associated stressors may be better able to buffer against stressors associated with human-induced climate change (Edgar et al. 2014; Jacquemont et al. 2022).

To ensure consistency among initiatives, efforts were made to utilize similar spatial datasets and follow analogous pre-processing methods, adapted to our focus on estuaries. Marine cumulative effects assessments in the Pacific Region do not delineate all estuarine habitat types specifically but include multiple habitats relevant to estuaries and this analysis. Extensive mapping efforts associated with cumulative impact mapping have generated datasets representing human activities, stressors (e.g., Weller et al. 2023), and benthic habitats (Agbayani and Murray 2023). In particular, the benthic habitat data and vulnerability scores used for marine cumulative effects assessments (Murray et al. 2024) include eelgrass, canopy kelp, mudflat, soft bottom intertidal, and soft bottom shallow habitats but not understory kelps, salt marshes, or tidal marshes. Where available, vulnerability scores provide important information that can help assess the influence of anthropogenic activities on habitats within individual estuaries. The results of this study suggested that estuaries associated with higher levels of activities (particularly those in cluster 1) broadly aligned with estuaries facing higher cumulative effects scores. The cluster analysis did not incorporate vulnerability scores to weight or rank the impact of activities, and therefore our results should not be interpreted as representing overall impact. However, the results can be used as a starting point to conduct a finer-scale cumulative effects assessment that incorporates vulnerability scores, or to assess the pathways of effects for key stressors within estuaries highlighted as having higher levels of activities. This work could include updates to spatial data and vulnerability matrices to include additional estuarine habitats, or estuarine species, to better detail their sensitivity to anthropogenic activities and stressors.

Activities within estuaries that support high salmon abundances may pose risks to salmon populations (Sharpe et al. 2019). Estuaries with higher degrees of habitat disturbance have been related to lower marine survival of Chinook Salmon (Magnusson and Hilborn 2003), and contamination of juvenile salmon is associated with industrial development within estuaries (Hodgson et al. 2020). Human activities have also been shown to impact heterogeneous habitats known to be important to salmon (Moore et al. 2010). Unsurprisingly, the largest estuaries on the BC coast, the Fraser, Nass, and Skeena, support the highest salmon biomass and richness based on escapement data. Cluster 1 estuaries also had high values for forage fish and Dungeness Crab metrics and 97% of cluster 1 estuaries had at least two intertidal biogenic habitat types present. Cluster 1 contains many estuaries with medium to large river systems (e.g., Fraser River, Skeena River) that are known to be important for fish migration and spawning. The Fraser River, for example, has supported the largest Sockeye Salmon runs in BC (Northcote and Larkin 1989; Burgner 1991). However, these estuaries have high numbers of both marine and terrestrial activities and higher projected stream temperature changes, which may impact salmon returning to spawn in the future. Walsh et al. (2020) suggested limits to future industrial activity and development in critical spawning, rearing, and migration habitats, such as estuaries, as a cost effective means of protecting salmon populations from further decline. Estuaries within cluster 1 could benefit from a coordinated management response focused on activities with direct impacts to specific estuarine habitats, and habitat mosaics, important to salmon, such as those proposed by Chalifour et al. (2022).

Some estuary-activity-fish associations also emphasize the need to focus on upstream habitat. Estuaries within cluster 1 scored high based on the overlay with salmon conservation units, a measure of salmon population diversity. Population diversity contributes to long-term sustainability of commercial species such as Pacific salmon and the stability of the ecosystem services to which they contribute (Moore et al. 2010; Schindler et al. 2010). This diversity may be increasingly important for species resilience with a changing climate (Darimont et al. 2010) and maintaining population diversity through future environmental changes depends upon continued availability of the habitats upon which they rely (Moore et al. 2010). Unsurprisingly, the estuaries with the highest counts of CUs were associated with large watersheds that extend inland, such as the Fraser and Skeena estuaries. The largest number of CUs with elevated conservation status were within the Fraser estuary, which has the largest watershed and substantial overlap with activities and stressors such as watershed development, agriculture, burned areas, and stream temperature change. The impacts associated with these activities within the watershed could affect not just the estuaries downstream but also spawning habitats within the stream network associated with the CUs. The geographies and associated activities of these estuaries emphasize that management strategies may need to vary between estuaries that drain large watersheds and have a distinct mix of terrestrial and marine activities, such as the estuaries in cluster 1, versus those that are primarily associated with small watersheds and only marine activities, such as those estuaries in clusters 4 and 5.

Habitat diversity and connectivity plays an important role in the conservation of biodiversity within estuaries (Chalifour et al. 2019). The time of year that juvenile salmon are resident in estuaries, length of residency, and estuarine habitat usage varies by salmon species and population (Weitkamp et al. 2014; Moore et al. 2016; Flitcroft et al. 2019), as well as the characteristics of the estuary, including its size and shape, and physical parameters such as salinity, temperature, and patterns of water flow (Thorpe 1994). Similar variation has been shown for forage species, such as Surf Smelt and Pacific Herring, and prey species including zooplankton (Arbeider et al. 2019; Sharpe et al. 2019). For example, while eelgrass beds are considered a highly important habitat for juvenile salmon, research within the Fraser River estuary found the greatest numbers of juvenile salmon in marsh habitats (Chalifour et al. 2019) and varying patterns of habitat preference have been found for fish and invertebrate species within and between estuaries and habitat types (Minello et al. 2003; Whitfield 2017). While the details of habitat associations and timing of estuary residence is not always well understood for many species, it seems clear that the exposure of juvenile salmon and other estuarine fish and invertebrates to estuary-specific activities and stressors will vary based on levels of activity, the environmental gradients and resulting mosaic of habitats within a given estuary, and how those habitats are used by the species.

Generally, all clusters had estuaries that contained most of the habitat types that we measured, and no cluster had exceptionally low mean intertidal biogenic habitat richness. While cluster 1 generally had lower individual values for some of the biogenic habitat features, such as those based on the Shorezone biobands, it had the highest mean richness value. However, because cluster 1 has some of the largest estuaries, the non-normalized biogenic habitat areas may be significant and may be exacerbated by missing information for some habitat types, such as tidal marshes. For example, there is high overlap of mapped eelgrass beds within the Skeena River estuary, which aligns with the relatively high level of survey effort within the area and the highlighted importance of eelgrass beds within the Flora Bank region of the estuary for juvenile salmon as well as zooplankton, Pacific Herring, and Surf Smelt (Moore et al. 2015; Sharpe et al. 2021). Cluster 1 was associated with the greatest number and magnitude of activities and therefore biogenic habitats within that cluster may be at greatest risk of degradation or modification. Cluster 4 had the lowest number of estuaries with multiple intertidal biogenic habitat types and only three estuaries with eelgrass or canopy kelp polygons. The 77 estuaries within cluster 4 were smaller (mean size of 4.0 ha) and were distributed across more remote locations and had lower levels of human activities. It’s difficult to determine how much the limitations and gaps in survey coverage influence these patterns as absences are not always noted and data were collected over a wide number of years and may not be representative of the current distribution of more ephemeral species, such as canopy kelps.

As was the case with the fish and fish habitat data, the clusters that are most important to waterbirds also tended to be the ones with the greatest number of associated activities. Estuaries considered most important for waterbirds (Pacific Birds Habitat Joint Venture Technical Team 2020) were found primarily in clusters 1 and 3 and included estuaries such as the Fraser with characteristic large tidal mudflats that are important staging areas for migratory shorebirds, such as Western Sandpiper (Vermeer et al. 1994). While cluster 3 estuaries had lower activity counts, estuaries within cluster 1 also included multiple activities, which may cause direct habitat degradation or modification within estuaries or surrounding delta areas (e.g., shoreline development, dredging, docks) that may be important for waterbird species. Further assessments could focus on measuring specific impacts from stressors relevant to priority species, such as those associated with shoreline development. The estuaries with the least importance to waterbirds were generally smaller with more rocky substrates. Describing the estuarine habitat associations for fish and invertebrate species considered Ecologically Significant (Gale et al. 2019) could help identify where priorities for fish and fish habitat protection align with the priorities of other agencies involved in estuary management, such as the PBHJV's work related to securing estuarine habitats for migratory birds. For example, management actions associated with migratory bird sanctuaries established in the Fraser estuary may confer habitat benefits relevant to that estuary's demonstrated importance for Pacific salmon based on escapement biomass calculated in this study.

5.2. CASE STUDIES

Counts of activities cannot give a complete picture of the associated stressors and potential impacts to estuaries, which are influenced both by the intensity and frequency of associated activities, as well as the physical characteristics (e.g., freshwater outflow) of an estuary that may influence the distribution of associated stressors and the potential cumulative nature of those stressors. To provide a picture of the distinctions visible at a more localized scale, we highlighted the Fraser and Skeena estuaries.

The Fraser and Skeena estuaries are both found at the base of large watersheds and are fed by vast networks of streams. However, the morphologies of the estuaries differ. The Fraser estuary is characterized as a drowned river valley (Emmett et al. 2000), with broad delta habitats and large salt marshes, such as those along Sturgeon Banks. The freshwater plume associated with the Fraser River generates estuarine conditions that extend beyond the estuary polygon used in this study, through the Strait of Georgia and out through the Strait of Juan de Fuca. The estuary is surrounded by a dense urban population and the delta habitats have been altered extensively for agricultural, industrial, or residential uses, and dikes and freshwater obstructions have altered estuarine circulation patterns (Groulx et al. 2004; Finn et al. 2021). Comparatively, the Skeena estuary is characterized as a fjard estuary, which is a shallower fjordal estuary fed by a large river system with extensive freshwater outflow (MacKenzie et al. 2000). The Skeena estuary has multiple bedrock islands that alter circulation and sedimentation patterns, large but less extensive sediment deposits than the Fraser estuary and large eelgrass habitats at Flora Bank (Wild 2020). The Skeena estuary has a smaller urban footprint but, like the Fraser estuary, is the location of large port facilities, with extensive shipping traffic and commercial anchorages in deeper waters.

The Fraser and Skeena estuaries were both found in cluster 1 and characterized by high numbers of activities (Figure 29, Figure 30). While the Fraser and Skeena both had 11 terrestrial activities present, the level of use (in terms of area or intensity) was usually 1 to 2 orders of magnitude higher in the Fraser watershed than the Skeena watershed. For example, there were 1,976 km^2 of agriculture in the Fraser and 60 km^2 in the Skeena. There were 356 freshwater obstructions in the Fraser watershed, and while the Skeena River itself is not dammed, there were 15 obstructions in other areas of the watershed. This aligns with recent research on freshwater obstructions and diking within the Fraser estuary which showed only 15% of floodplain fish habitat remained accessible (Finn et al. 2021). The Fraser and Skeena estuaries also had similar counts of marine activities (17), but the activities present were not the same. For example, activities exclusive to the Skeena estuary included recreational anchorages, recreational groundfish fishing, commercial hook and line fishing, and floating homes and lodges. In part, some of the activities not reflected in the Fraser estuary may be due to a spatial data gap (e.g., recreational anchorages are likely in an estuary with a large urban population) and potentially activity counts in the Fraser are under-represented.

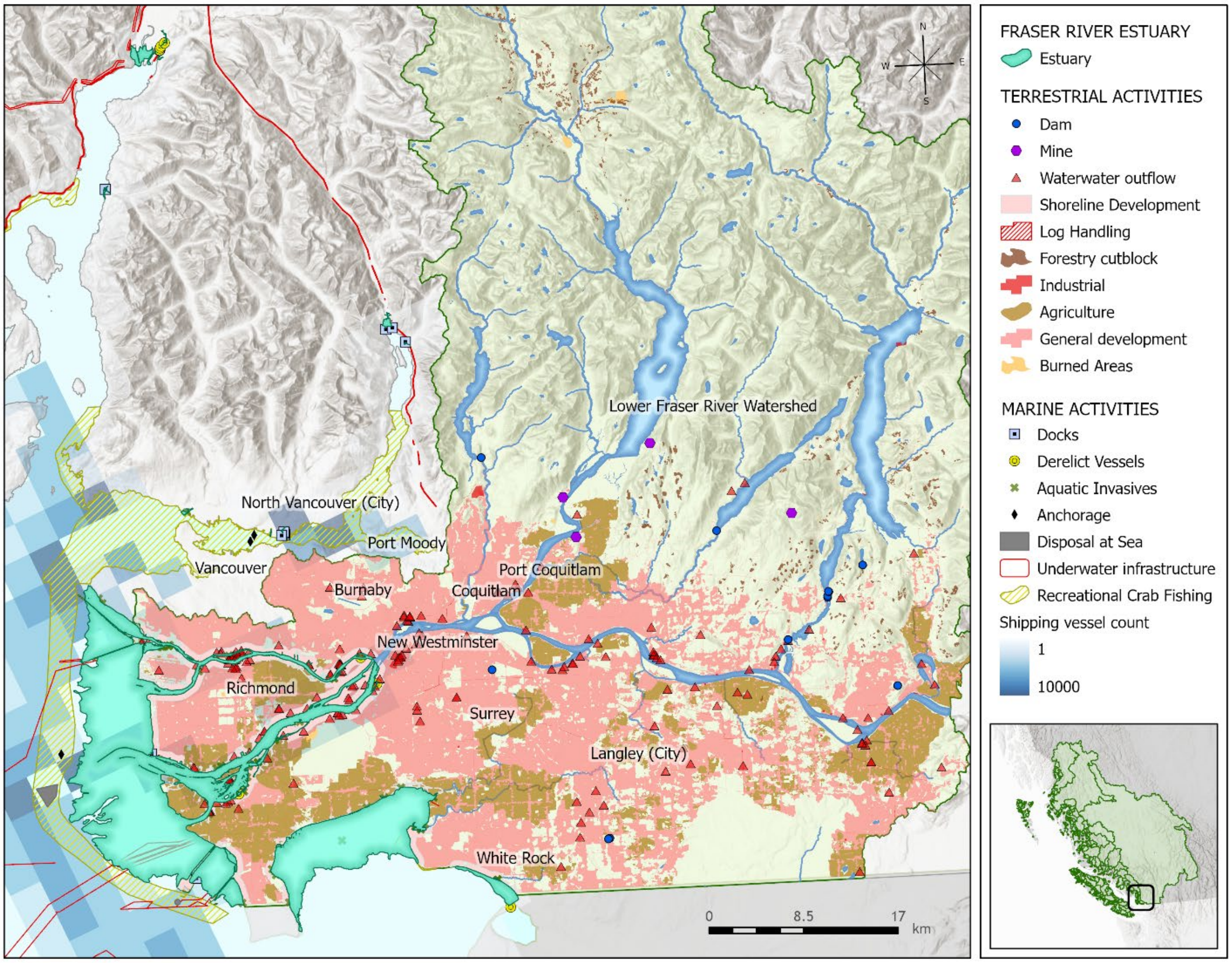

Figure 29. Spatial data for activities within the Fraser estuary. To facilitate visualization, the map focuses on the estuary itself and only a portion of the watershed is displayed. The following activities are not shown due to data sharing restrictions, because they are not visible at this scale or map extent, or because of a high number of overlapping gridded datasets: dredging, recreational boating traffic, commercial fishing activities, and freshwater obstructions.

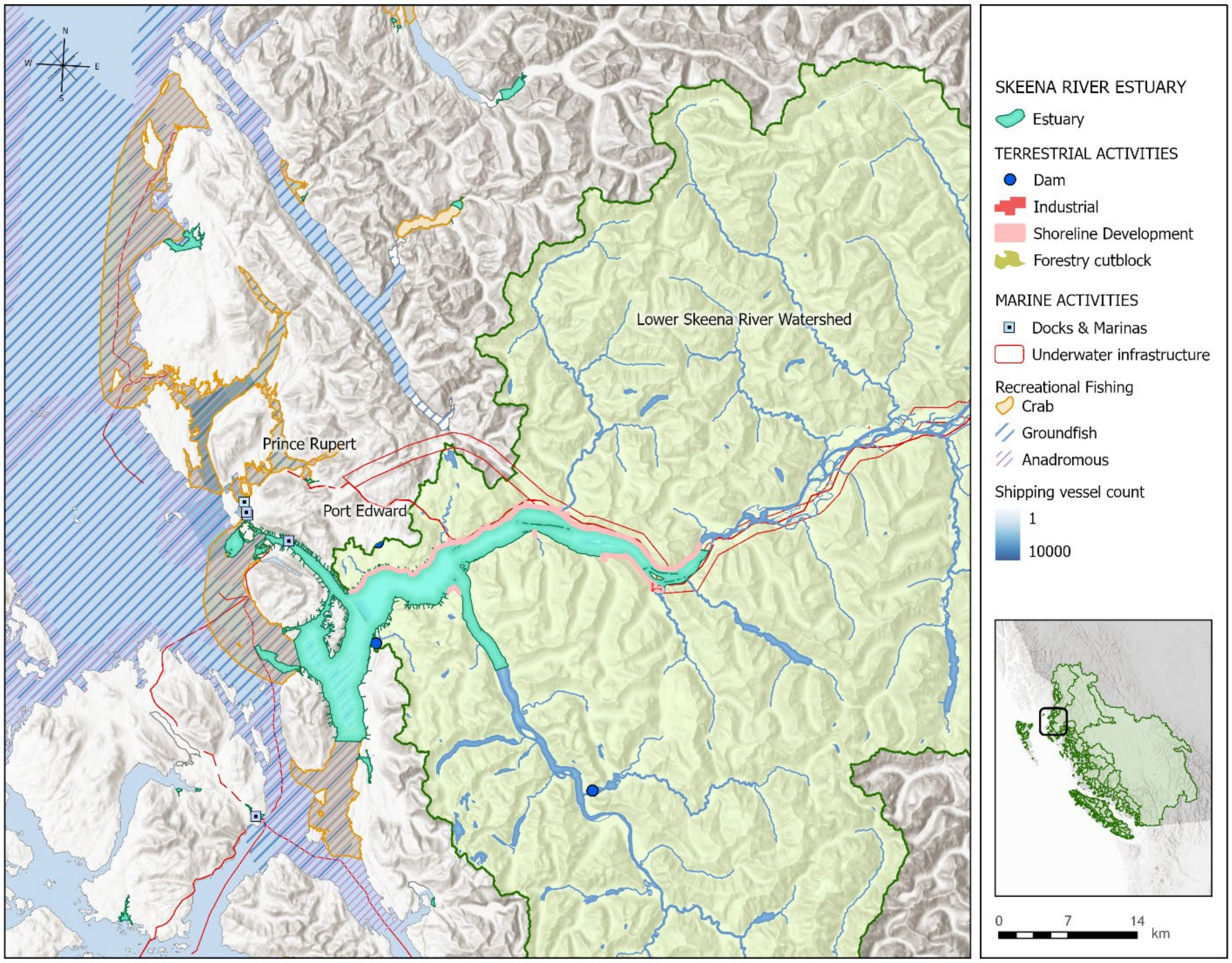

Figure 30. Spatial data for activities within the Skeena estuary. To facilitate visualization, the map focuses on the estuary itself and only a portion of the watershed is displayed. The following activities are not shown due to data sharing restrictions, because they are not visible at this scale or map extent, or because of a high number of overlapping gridded datasets: dredging, recreational boating traffic, recreational anchorages, floating structures, log handling, agriculture, mining, development, burned areas, commercial fishing activities, and freshwater obstructions.

Stressors associated with human-induced climate change also showed differences in the Fraser and Skeena estuaries (Figure 11). Both estuaries were projected to have higher levels of sea level rise, with projected changes in the Fraser estuary somewhat greater. Air and stream temperature changes were projected to be moderate in both estuaries, though again higher in the Fraser. Precipitation change was projected to be lower in the Fraser estuary and moderate in the Skeena estuary. Based on results from a cumulative effects analysis that incorporated habitat vulnerability into activities[3], activities present in the Skeena may have less of an impact on estuarine habitats compared to activities present in the Fraser. Notably, while both estuaries had higher cumulative effects scores, the scores associated with the Fraser estuary were twice those of the Skeena estuary.

5.3. RELATED WORK

We conducted this assessment of BC estuaries based on anthropogenic activities as a first step to aid managers in prioritizing particular estuaries for heightened management action related to fish and fish habitat protection. Activities and stressors identified through the literature review have similarities with those assessed in other estuarine studies. We did not conduct a full cumulative effects or ecological risk assessment; however, we did attempt to align our approach with ongoing cumulative effects research in our region, both at a coastwide scale (as mentioned previously) or within individual watersheds. Linkages exist with ongoing work related to cumulative effects in more localized settings as well as research on the importance of estuaries for Pacific salmon.

5.3.1. Estuary Activities and Stressors

Many of the activities incorporated in the current analysis align with those described in conceptual models of estuaries across BC (Jeffery et al. 2023), for salmon habitats within the Skeena estuary (Pickard et al. 2015), and for large estuaries in Washington State (Andrews et al. 2013). For BC estuaries, watershed and shoreline activities such as forestry, mining, industry, agriculture, pulp mills, ports, and communities were highlighted, along with marine activities focused on aquaculture, recreational boating, and commercial or recreational fisheries, and stressors associated with human-induced climate change (Jeffery et al. 2023). In the Skeena estuary, Pickard et al. (2015) noted marine vessel traffic, species harvest, shoreline and nearshore development, wastewater discharges, ocean dumping, dredging, invasive species, marine forestry activities, and human-induced climate change. In addition, information on predation, disease, and competition with hatchery-raised fish were incorporated. In Washington, human pressures identified for estuaries also included activities and stressors originating in watersheds, such as nutrients and pollution, shoreline modification, and sediment and freshwater inputs, along with extraction associated with fishing and shellfish aquaculture, and marine activities such as commercial shipping, dredging, invasive species, and seafood demand (Andrews et al. 2013). Spatial datasets suggested to represent activities were similar to this study (e.g., modified shoreline area, vessel traffic). However, in Washington, dredged volumes were suggested, which may be more representative of the extent of dredging activities than the point or polygon data available for this study, and reservoir capacity was used to show potential reductions in freshwater and sediment flow beyond the number and location of obstructions.

Regional assessments for estuaries in the United States have also incorporated similar suites of activities and stressors. Habitat modification, freshwater flow changes, sediment contamination, and invasive species were identified as concerns for estuaries along the West coast (Emmett et al. 2000). Freshwater obstructions, shoreline development, dredging, and activities causing pollution sources or the introduction of invasive species, are highlighted along with human-induced climate change by the National Estuary Program in the United States[6]. An assessment of estuarine habitats in 196 estuaries across the United States also included similar stressors, focusing on four indicators: land use, alteration of stream flows, pollution sources, and eutrophication (Greene et al. 2015). Similar to this study, spatial datasets representing land use classes and the location of pollution sources were identified and scaled based on the size of the watershed or shoreline area within which they were found, and suggestions to refine land use data in estuarine and shoreline areas aligns with this study's inclusion of the Shorezone database's manmade coastal classes. In Greene et al. (2015), alteration to stream flow was assessed using the density of upstream dams, similar to this study, but also integrated flow data obtained from upstream surface water gauges for many of the estuaries. Spatial data for

[6] US Environmental Protection Agency. How the National Estuary Programs Address Environmental Issues.

eutrophication were not broadly available but eutrophication was found to be correlated with spatial data for watershed pollutants, land use, and river flow (Greene et al. 2015).

5.3.2. Freshwater Cumulative Effects

Our results place the Fraser Estuary, which is experiencing numerous stressors from anthropogenic activities occurring within its watershed, in cluster 1. A detailed cumulative effects assessment was conducted recently in the Fraser Valley (a smaller extent of the Fraser River watershed) to determine terrestrial stressors for at-risk fish species such as Sockeye and Chinook Salmon, White Sturgeon, and Nooksack Dace (Boyd et al. 2022). Eleven activities that disturb the landscape and have potential downstream impacts, such as roads, agriculture, and urbanization were linked to seven habitat stressors (threats): pollution, habitat destruction, riparian disturbance, sedimentation, habitat fragmentation, nutrients, and aquatic invasive species. Spatial data for activities were combined to generate spatial layers specific to each stressor. Our analysis used similar activities (except for freshwater invasive species) and spatial datasets and linked the activities to similar stressors (e.g., agriculture was linked with increases in the downstream flow of nutrients; Section 2.2.1.2). However, following the approach used in marine cumulative effects assessments, we did not group activities prior to analysis and results remained summarized at the activity level.

Novel in the work by Boyd et al. (2022), was the development of a flow accumulation model to assess cumulative effects for individual stream segments. For a given stream segment, the area of upstream stressors was totaled and then divided by the area of the upstream catchment. By dividing by upstream catchment area, threats become diluted. This approach allowed for the assessment of stressors to fish populations at specific points in the stream network. We used a similar methodology, but since we were interested in the final outflow point into an estuary, the activity or stressor value was divided by the entire watershed area, as has been done for marine cumulative effects assessments (Clarke Murray et al. 2015). Boyd et al. (2022) found pollution, riparian zone disturbances, and sediment as the prominent contributing stressors to fish habitat. Similarly, we found multiple terrestrial and marine activities related to sedimentation, pollution, and habitat modification stressors associated with cluster 1, which included the Fraser estuary (Figure 2, Table 3).

Given the large size of the watersheds in our study, integration with future developments to freshwater cumulative effects work, such as a planned expansion of the flow accumulation model to other areas of the BC coast (J. Iacarella, DFO, pers. comm.), could provide a better understanding of how threats dilute throughout the watershed. Further, future assessments for estuaries could benefit from better understanding of how lakes that intersect a stream network may act as sediment and nutrient traps, potentially diluting the stressors associated with activities that cause sedimentation (Myers et al. 2007). This could alter the range of influence of landscape disturbances occurring distant from the ocean in very large watersheds such as the Fraser River.

5.3.3. Estuaries and Pacific Salmon

Additional research has been conducted in an effort to improve habitat conditions in support of Pacific salmon populations. An example with a particular focus on investigating resilience to climate change and associated sea level rise, the Nature Trust of BC has been working with Indigenous, non-profit, academic, and other government partners to monitor 15 estuaries across the BC coast[7]. Restoration efforts focused on activities and stressors included in this study are also underway within two estuaries on Vancouver Island. Within the Cowichan-Koksilah estuary, the use of dikes to facilitate log storage and handling operations altered estuarine circulation patterns. Working with the Cowichan Tribes and other groups involved in the estuary's management plan, barriers are being removed to restore freshwater flow and improve marsh habitats[8]. In the Nanaimo estuary, freshwater flow had also been disrupted due to industrial and agricultural activities and the Snuneymuxw First Nation is working with partners to remove agricultural berms to restore flow patterns and restoring habitats such as tidal marshes[9].

At a broader scale, indicators have been proposed for monitoring fish habitat in support of Canada's WSP. The WSP (DFO 2005) focuses on restoring and maintaining diverse wild salmon populations and requires the selection of indicators to help assess stream, lake, and estuary habitats within salmon CUs and evaluate changes over time. Indicators selected through a consultative review process (Stalberg et al. 2009) include pressure indicators that describe stressors, typically associated with human activities, that could be monitored over broader regions. State indicators describe the status of the estuarine environment and focus on locations of potential concern identified through evaluation of the pressure indicators. Selected estuary and stream pressure indicators relate to activities examined in this study, including marine vessel traffic, discharges of pollutants, and activities that cause habitat modification within estuaries, as well as activities in watersheds that impact streams and habitats downstream, such as land cover changes, road development, and pollutant discharge. While fewer activities were included, monitoring of state indicators related to abiotic conditions within an estuary may provide information on other stressors. For example, monitoring of contaminants and dissolved oxygen levels could identify the frequency of hypoxic events that are exacerbated by anthropogenic nutrient loading due to wastewater discharges or agriculture, and the development of appropriate datasets. As such, the indicators developed for Pacific salmon can be an important contribution to future local-scale estuary assessments for other species. Fish habitat information included in this study (Section 4.3.4) is related to additional estuary indicators, in particular the quantification of habitat area for marshes, eelgrass, and mudflats. As in this study, issues of resolution and data gaps in finer scale habitat information were noted as challenges for coastwide or regional assessments and changes in coverage of tenure areas were proposed as a proxy for assessing gains or losses of fish habitat (Stalberg et al. 2009).

5.4. LIMITATIONS AND UNCERTAINTIES

5.4.1. Literature Review

In synthesizing the literature on anthropogenic activities and their impacts on estuary systems from the articles and reports that came out of the literature review, notable gaps were found. These gaps may be the result of our search criteria, including habitat-specific search terms and the time period for publication, or a research gap in estuary science within the Pacific coast of North America. The time period used in the review was limited (2010–2022), and misses earlier foundational work on the impacts associated with long-running activities on the BC coast, such as forestry or fishing. For example, potential estuarine impacts of forestry activities were documented extensively in Levings and Northcote (2004) and earlier research in estuaries near

[7] Enhancing Estuary Habitat & Sustaining Coastal Wildlife | Estuary Resilience

[8] Cowichan Estuary Restoration Project | Estuary Resilience

[9] Restoring the Nanaimo River Estuary | Estuary Resilience

Kitimat showed higher abundances of Dungeness Crab and Sunflower Sea Star in estuaries that had not been used for log storage and handling (Picard et al. 2003). However, while these activity-stressor linkages may not have been identified in the literature review (Figure 2), these activities were mapped and were not excluded from the analyses.

Additionally, because of the aforementioned limitations of the search criteria, the full complement of research on a subject could be missed. For example, the extent to which aquaculture contributes to sea lice transmittals is oceanographically (Brewer-Dalton et al. 2015) and environmentally (DFO 2023c) dependent, and pathogenic effects on salmon may vary by species (Saksida et al. 2015). Other knowledge areas that were missing from the literature review include research into the stressors associated with fisheries, eutrophication associated with development and pollution within the estuary and watershed, and the pollution generated from vessel traffic either as organic/inorganic inputs or noise. Yet we know that these activities have impacts on marine environments (e.g., Erbe et al. 2014; Clarke Murray et al. 2015; Fox et al. 2016), and occur adjacent to estuaries included in this study, such as large vessel anchorages near the Cowichan-Koksilah estuary (Murchy et al. 2022). For example, research on the effects of anthropogenic noise on Pacific salmon and herring showed heightened anti-predatory behaviour (van der Knaap et al. 2022). Vessel traffic and coastal infrastructure, such as docks, floating lodges and homes, derelict vessels, and aquaculture gear, are vectors for invasive species introductions (Iacarella et al. 2019; Iacarella et al. 2020). Further, the differential impact of fishing gear (commercial or recreational) to estuarine habitat via benthic contact and damage or abandoned ghost gear was not mentioned in any of the articles. The review also did not include differential effects of climate change on fish communities. For example, mixed effects of sea surface temperature have been found for juvenile fish in Clayoquot and Barkley sound eelgrass beds during a marine heat wave (Robinson et al. 2022). More specific examples of highly impactful activities in estuarine systems were also omitted from the review, including the effects of grubbing by Canada Goose, a formerly rare overwintering species whose numbers have increased significantly, and the subsequent removal of vegetation in some estuaries on eastern Vancouver Island (Dawe et al. 2011; Dawe et al. 2015). Further, because anthropogenic activities were the focus of this study, impacts associated with changes in estuarine community composition, such as rising salmon predation due to increasing Harbour Seal populations, were not considered but have been investigated by others (e.g., Salish Sea Marine Survival Project[10]) and could be important to incorporate in future work.

Consequently, we acknowledge that additional activities and stressors likely exist that influence estuarine environments and could be characterized based on research from marine studies or studies focused on specific estuarine species. Within this analysis we limited the activity choices to those identified through the literature review (while we did use multiple specific layers for very broad activity types) and constrained the stressors list to those that are proximally generated by the activity and documented within the review, although we understand there may be more. This review does give some indication of the activities tied to the greatest array of stressors. Future reviews could include a longer date range as well as search terms for individual species to capture a broader list of potential activities and stressors, which could inform future assessments that may incorporate the direction or degree of impact associated with the different activities. For example, a comprehensive assessment of estuarine fishes and invertebrates along the west coast of the United States (Emmett 1991) could inform potential impacts to species from the related stressors incorporated in this study.

[10] Salish Sea Marine Survival Project. Research Findings.

5.4.2. Spatial Datasets - Activities

Spatial datasets compiled for this analysis are similar to those suggested for representing activities in other estuaries and face similar issues of data extents, gaps, currency, quality, and resolution (Andrews et al. 2015; e.g., Greene et al. 2015; Pickard et al. 2015). The spatial extent of the activity datasets did not always overlap with all estuaries. For example, Long Lake estuary, which is part of Wyclees Lagoon off Queen Charlotte Strait, was likely not included in the extent of much of the marine activity data, as Wyclees Lagoon may be considered a lake or tidal basin. However, this is a remote and isolated part of the coast, and it is likely that activities and stressors are minimal. In addition, the sea level rise data did not extend up Portland Canal on the northern border between BC and Alaska or to the end of Dean Channel on the Central Coast. We assigned the closest values for the estuaries in these locations. A lack of survey effort likely also limits the completeness of some datasets, including counts of aquatic invasive species such as European Green Crab (Howard et al. 2019). Since the time of review, the Canadian Aquatic Barriers Database[11] has been developed that incorporates additional regional and site-specific freshwater obstructions and dams datasets that supplement those included in this analysis.

There was also activity data with inconsistent temporal coverage or for which only older information was available. The spatial data for recreational fishing were collected through surveys with fishers over a decade ago (British Columbia Marine Conservation Analysis (BCMCA) Project Team 2011) but remain the best information available. The Shorezone data used to identify coastal man-made structures was collected at different times, with the oldest data being collected in 1991 in southern Haida Gwaii and some southern areas of the coast being updated in 2021. Therefore, the existence of older features is less certain, a challenge noted in other studies (e.g., Greene et al. 2015), and newer developments may be missed. However, the inclusion of additional data sources supplements information related to shoreline development available from the Shorezone.

We were not able to include some of the stressor data for human-induced climate change, such as ocean acidification, stream flow, and changing sea surface temperatures, as the data were either unavailable, did not extend across the BC coast, or were at too coarse of a spatial resolution. Imaging technologies such as LiDAR may be important survey tools for developing higher resolution estimates of habitats vulnerable to sea level rise or areas that can facilitate the migration of estuarine habitats (Flitcroft et al. 2018). Hydrologic modeling of freshwater outflow (e.g., Morrison et al. 2012; Schnorbus et al. 2014) can also help characterize circulation patterns within estuaries, and associated temperature and salinity gradients, now and in the future as outflow from coastal rivers may become more variable and increasingly influenced by rainfall with a warming climate.

We lacked data to quantify certain activities beyond area-based measurements of occurrence or capture the extent, intensity, or frequency of their presence within estuaries. For example, the recreational fishing datasets did not include catch values and are represented by the broad areas known to be important for fishing activities (British Columbia Marine Conservation Analysis (BCMCA) Project Team 2011). Tenures associated with log handling or aquaculture may have variable levels of use depending on the status of operations within a given region. Further, some stressors associated with log handling, such as shading of eelgrass or other estuarine vegetation (Levings and Northcote 2004), may also not be as permanent as those associated with other forms of habitat modification, such as the creation of armoured shorelines.

[11] Canadian Wildlife Federation. Canadian Aquatic Barriers Database.

Development of a proposed model to estimate deposition associated with log storage operations (Stalberg et al. 2009) would further understanding of impacts for fish and fish habitat relevant to this study.

Certain activity datasets had quality or resolution issues that created uncertainty. The spatial data used to represent agriculture and a portion of the general development activities were generated from remotely sensed imagery where the classification of land-use type was based on a global land classification model (see Table 1). The results appear mostly accurate for BC based on a manual visual comparison to recent satellite imagery, but there is some uncertainty around the classification of smaller agricultural areas in coastal and mountainous areas that appear as clearings. Commercial catch data were available at relatively coarse resolution of 1 km^2 for analyses focused on estuaries with a median size of 0.22 km^2. These data may overrepresent their overlap with estuaries for certain gear types. For example, there was minor overlap of the commercial trawl fishery with estuaries, though we would not expect this activity to be present. This activity was not significantly associated with any cluster but future analyses could restrict the coarser datasets based on known fishing depths or management areas, as has been done for some projects (Clarke Murray et al. 2015). The values from the wastewater outflow dataset are modeled values current to 2017 based on data from a variety of sources, including provincial waste discharge authorizations and ECCC combined sewer outflow volumes. The dataset contains various structures related to wastewater (e.g., treatment plants, individual outflow pipes). There is uncertainty whether every feature flows directly into water or if it is land-based with no marine component. Therefore, we only included structures that overlap with estuaries and the shoreline zone even though some outflow areas may empty directly into the ocean and spread to a distant estuary. Lastly, the locations of some activities were represented as lower order geometries (i.e., points) as opposed to polygons that represent the actual footprint of an activity. This required changing the geometry type in order to be combined with a similar but higher order geometry dataset. For example, dredging points for small construction projects were buffered by 50 m so that they could be combined with a dataset of larger dredging polygons for boat channels. This was also the case with the shoreline and general development datasets in which points (e.g., log sorts) and linear features (e.g., roads) were buffered to polygons so that they could be combined with other polygons. The buffers applied were estimates of the activity/structure footprint based on past assessments (see Table 1) but may not accurately represent all features.

5.4.3. Spatial Datasets – Fish and Fish Habitat

Spatial data were not available to inform all of the estuarine fishes and invertebrates identified as Ecologically Significant or estuarine habitats. Additional data for some of the fish species can be found in data sources such as the species-specific Important Areas delineated during EBSA development (Clarke and Jamieson 2006a; Jamieson and Levesque 2014; Levesque and Jamieson 2015). The resolution of the data is not always fine enough to encompass the estuary polygons but, for some estuaries, there may be overlapping Important Areas for some species. For example, Important Areas identified for spawning and rearing aggregations of Walleye Pollock overlap with the Fraser River, Bottleneck Inlet, Carter River, and Kwinamass River estuaries. Additional overlaps may be relevant along the West Coast of Vancouver Island for Pacific Hake, Lingcod, Green Sturgeon, juvenile flatfish, and Pacific Sand Lance. While Important Areas were delineated for Longnose Skate within inlets of WCVI and SOG, attributes note that the areas pertain to deeper waters. Important Areas with potential and confirmed Pacific Sand Lance habitat may also fill gaps until additional species distribution models (SDMs) are developed outside of the SOG. The recent evaluation of potential SeBAs in the Strait of Georgia identified several Important Areas as potential SiBAs at a broader bioregional scale, including canopy kelp and eelgrass, though their sensitivity and resilience to fishing pressures was not assessed (DFO 2019b). Validating the Important Areas for benthic species with updated data and utilizing SDMs to identify areas with high probability of suitable habitat for benthic species, including those found in estuaries, was recommended (DFO 2019b).

While the NuSEDS data provide valuable historic salmon population data, there are limitations and caveats in terms of data interpretation for salmon escapements. Over the years there have been variability in the sampling effort and spatial coverage, as well as in the systematic retrieval of observations from streams in BC and the Yukon, and methods for inventorying fish escapement have not been consistent across the time series (English 2016; DFO 2022). Missing records in NuSEDS may signify that no data exist, or that data have not been received (DFO 2022), and not all streams associated with the estuaries included in this study have been surveyed. As such, the estimates potentially underestimate the total biomass and number of species that pass through each estuary. While the geographic and temporal variability of survey effort requires utilizing NuSEDS data with caution, in general the escapement enumeration data are useful for determining species presence and abundance values at a decadal time scale (DFO 2022), but less appropriate for investigating year-to-year variation in population or stream/estuarine habitat use. The estimates may also not provide the historical context for the size and diversity of salmon populations that may have used each estuary prior to 1990. That historical context could be an important additional consideration for restoration activities.

As has been identified in other analyses (e.g., Hughes et al. 2014), spatial information was lacking for many of the non-commercial species, including those considered Ecologically Significant such as Shiner Perch, Nuttall's Cockle, and Sunflower Sea Stars. Given that non-commercial species are not the focus of surveys conducted for stock assessments, less may be known about their status and spatial data may be scarce. However, these species are noted in biodiversity surveys, including beach seine and environmental DNA (eDNA) surveys, as well as multispecies dive surveys that document benthic habitats and species in nearshore environments along the BC coast (Davies et al. 2018). eDNA surveys have been used to better understand community assemblages within eelgrass (He et al. 2022), fish abundance and biomass within estuaries (Stoeckle et al. 2017; Rourke et al. 2021), and population trends of anadromous fish (Pochardt et al. 2020). In addition, estuary-specific research has been completed that contains valuable information on the distribution of commercial and non-commercial species. For example, investigations of fish communities in the Skeena estuary provide important information on Pacific salmon, forage species such as herring and smelt, as well as key invertebrate prey species (Sharpe et al. 2021).

Spatial and temporal gaps also exist for datasets informing fish habitat, including eelgrass and macroalgae, salt marshes, and tidal marshes. The variation in temporal coverage mentioned for the coastwide Shorezone aerial surveys suggests that groundtruthing may be important, particularly for more ephemeral habitat features (e.g., canopy kelp species). The linear nature of the Shorezone data may also miss important details on the extent of some habitat types (e.g., the linear data may not aptly characterize the wide salt marsh areas found in the Fraser estuary compared with narrower bands of salt marsh present in the Skeena estuary). However, spatial information from localized surveys that more specifically delineate the quality and quantity of biogenic habitats (e.g., polygons representing eelgrass beds) is also limited in many regions, and of varying currency, and may only note the presence of features but not confirmed absences (Figure 31). Further, as noted previously, tidal marsh information was only available for a few estuaries included in this study. More comprehensive habitat maps are available for some estuaries that have been the site of research or planning initiatives and could be used in the future to supplement coastwide datasets. For example, the Fraser estuary was mapped extensively to inform development applications during FREMP and, while the data are not current, they could be a source of missing habitat information for salt and tidal marshes (Fraser

River Estuary Management Program 2003). Comprehensive habitat maps have also been developed for the Cowichan-Koksilah estuary in support of restoration and conservation efforts[12] and delineate the habitat features included in this study. Detailed substrate information has been collected as part of research to understand the hydrodynamics and morphology of the Skeena estuary (Wild 2020). Coordinated regional survey efforts can also help fill gaps, such as the kelp monitoring program advanced by the Hakai Institute and Marine Plan Partnership[13], as can recent progress on coastwide species distribution models (SDMs) (e.g., Nephin et al. 2020). Of particular relevance to evaluations of fish habitat within estuaries is the ongoing development of an eelgrass SDM and the potential development of a salt marsh SDM (A. Park, DFO, pers. comm. 2023).

[12] Cowichan Estuary Restoration & Conservation Association. 24 December 2017. Christmas 2017 Letter from the Chair.

[13] Marine Plan Partnership (MaPP). 2019. Helping the Kelp.

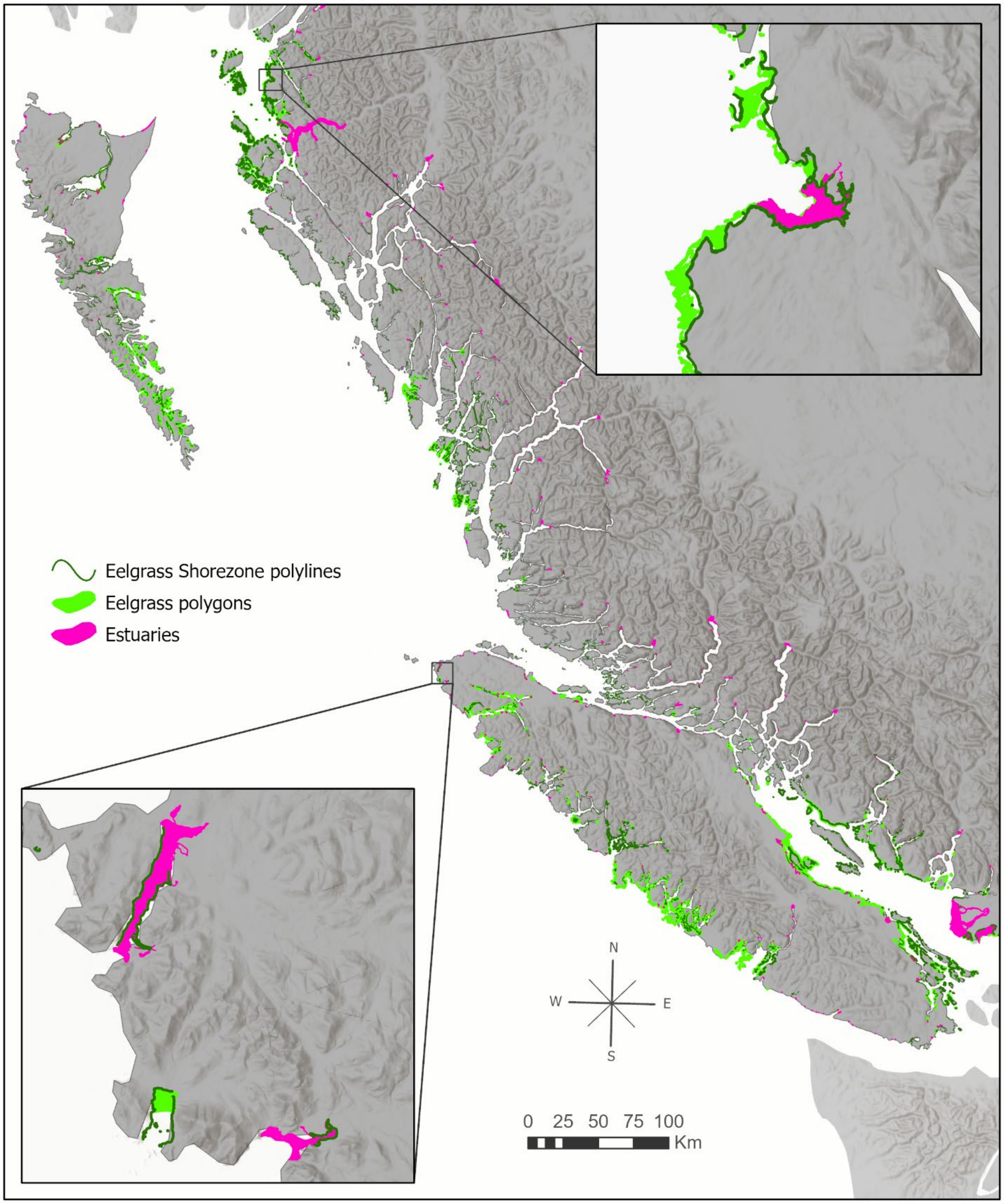

Figure 31. Distribution of eelgrass bed information along the BC coast based on the Shorezone eelgrass biobands and compiled polygon datasets. Inset maps show locations where the two datasets coincide and where information is available from only one source.

5.4.4. Analysis Methods

Several assumptions were inherent in estimating the spatial relevance of anthropogenic activities to estuaries. Modeling the spread and decay of stressors from marine activities required converting data to raster format. While we used a relatively high-resolution cell size (100 m), this may still generalize narrow and small areas of estuaries. Projecting the range of influence of an activity was done as a linear decay over 10 equally spaced rings around a feature. There is limited information on how stressors decay in estuarine and marine environments, and we may be over/under-estimating values at certain points. In addition, for large buffers, 10 steps may not create a continuous enough rate of decay. Lastly, disconnected pieces are created when buffering a feature and erasing the portions of the buffer that overlap land. While we removed these disconnected pieces from the analysis, modeling the flow of a stressor around land features is complex, and buffers that wrap around a land feature but remained connected may overestimate potential impacts to an estuary. Nearshore and estuarine circulation models would help understanding of the movement of estuarine stressors.

While most activities were represented individually, some of the terrestrial activity data were merged into general development datasets (i.e., industry, shoreline, general). This follows methodology similar to Boyd et al. (2022) in which activities were merged based on the stressors (threats) they produce (e.g., mining and urbanization both create pollution). However, through this generalization we may be missing more specific but distinct stressors. For instance, different types of mining may produce different types of pollution that generate variable species responses. However, information is lacking on species- and habitat-specific vulnerabilities and pathways of effects, as was also shown in our literature review. As this was intended to be a preliminary analysis of estuaries at a coastwide scale, we believe merging similar data related to development and industrial projects is useful for general interpretation. However, it may also require a bit more post-hoc interpretation to isolate the source activities that are most directly relevant to management activities in a given estuary.

We log transformed watershed areas to achieve a normal distribution of areas, but we did not log transform estuary areas. The range of watershed areas was much greater than estuary areas, with the Fraser watershed (the largest watershed) six orders of magnitude larger than the watershed for the Lipsett Creek estuary (the smallest watershed) (Figure 3, Table C1). We also made the assumption that a stressor in an open marine system would decay linearly, whereas a stressor in a dendritic system would scale non-linearly. This has the effect of narrowing the range of the dilution effect of watershed area so that the activity values in the largest watersheds are not always the lowest adjusted values. However, we are uncertain of this relationship, and this study would benefit from a better understanding of how different stressors generated from watershed activities dilute in marine and freshwater environments.

The stressors associated with terrestrial activities in our analysis were only estimated for the immediate downstream estuary, and we did not estimate the spread of stressors from terrestrial activities in the marine environment to other nearby estuaries. Clarke Murray et al. (2015) used a threshold of the distance of an activity to the coast to scale the intensity value of the activity, and the stream order of the watershed determined how far the stressor would spread. However, they only analyzed watersheds with a stream order of 7 or higher. This study analyzes all watersheds with streams of 4th order or higher, but there is uncertainty in how far stressors would spread in the ocean from lower order streams. Given the 439 estuaries spread throughout the coast, a more advanced version of our study would require analyzing outflow for nearly every coastal watershed that is within the range of influence of the terrestrial activities at the point of outflow.

5.4.5. Fish And Fish Habitat

Species lists used to inform this study were taken from estuary management plan documents and research associated with those estuaries (Table 2, Table D1) and are consistent with lists developed for estuaries along the west coast of North America (Emmett 1991) and indicator species identified for large estuaries in Washington State in support of MSP (Andrews et al. 2015). For example, zooplankton, burrowing shrimp, oysters and clams, Dungeness Crab, resident estuarine fish, sturgeon, and Pacific salmon were proposed as indicators of Washington State estuaries and, similar to the data compiled for this study, escapement biomass was suggested as the Pacific salmon indicator. Additional species pertinent to estuary management may be found in localized research in other estuaries and relevant nearshore habitats in BC (e.g., eelgrass meadows (Robinson et al. 2011; Robinson and Yakimishyn 2013)). The species considered Ecologically Significant for this work were taken from an assessment conducted at a bioregional scale (Gale et al. 2019) that considered a broad suite of coastal and offshore ecosystems but did not assess all species known to reside in BC estuaries. As such, the estuary-specific importance of some species, particularly those at a lower trophic level, may be understated in this work despite their importance in estuarine food webs and their role as potential indicator species. For example, in a study that showed increasing homogenization of fish communities in eelgrass beds in areas of high anthropogenic disturbance, Threespine Stickleback and Sharpnose Sculpin were found to be indicators of high disturbance sites (Iacarella et al. 2018). Threespine Stickleback was also suggested as an indicator of water quality in Washington State (Andrews et al. 2015). White Sturgeon are another example of a species that was not assessed within the context of developing ecological conservation priorities for the NSB (Gale et al. 2019) but is a commercially important species found in the Fraser estuary. White Sturgeon feed on higher trophic level fish species such as Pacific salmon, which was a consideration for fulfilling the role as an upper-level predator, one of the ecological roles assessed for Ecologically Significant Species (Gale et al. 2019). While their marine migrations are not well understood (DFO 2023b), White Sturgeon may also meet the nutrient transfer criterion for ESS. White Sturgeon has been assessed as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and several populations have also been listed under Canada's *Species at Risk Act* (DFO 2023b). Among the challenges noted in the recovery strategy for White Sturgeon are loss of habitat quality within estuarine environments due to anthropogenic activities and reduced food supplies due to fishing, habitat disturbance, and climate change (DFO 2023b). Habitat trends point to the influence of changes to drainage patterns and higher levels of pollutants due to urbanization within the Fraser estuary. A list of fish and invertebrate species captured in estuary management plans but not identified as ESS to date has been compiled that can inform future work (Table D1).

Ecological metrics have been compiled and compared to the estuary clusters resulting from this analysis of anthropogenic activities. Given the incomplete and dated information available for some of the fish and fish habitats, in particular those related to habitats and non-commercial species, and the potential correlation in some metrics, an attempt was not made to combine the fish and fish habitat information together with the activity data into a single analysis. Similar challenges have been noted for combining data on pressure, state, and habitat indicators to evaluate the overall status of a given salmon CU (Stalberg et al. 2009). However, other analyses have used ecological metrics alone to develop a classified ranking of estuaries. In particular, the estuary rankings for waterbirds were derived from a biological importance score using an additive approach and expert-derived weightings to reduce the impact of potential correlation and focus the scores on the variables with the most confidence (Ryder et al. 2007; Pacific Birds Habitat Joint Venture Technical Team 2020). A similar approach has not been tested in this work but could be attempted using the compiled metrics and incorporating the guidance of experts and priorities set by FFHPP and partner groups.

6. NEXT STEPS

This analysis provides an initial assessment to help focus further estuarine conservation and management efforts. Recommended next steps in the process include building collaborations to help set priorities, collecting more comprehensive and finer scale species and habitat data, furthering understanding of the habitat use of different species and the impacts of the activities and stressors on fish and fish habitat, and designing finer scale assessments of estuary risks and cumulative effects.

The predominant activities associated with the estuary clusters revealed in this study can help guide partner engagement for more localized estuary management and conservation. The land-sea interface has been highlighted as a conservation challenge due to the multiple ecological and jurisdictional boundaries involved (Sloan 2007) and improved partnerships are often highlighted as integral to future planning (Greene et al. 2015). Collaboration and integration with federal and provincial agencies, Indigenous governments, and stakeholders, as has been demonstrated through the estuary resilience projects[14], are important components for the effective protection of fish and fish habitat because stressors arise from activities regulated by a variety of different groups (DFO 2005, 2019a). Collaboration and stakeholder buy-in were also a key recommendation from a review of estuary management planning in BC (Williams and Langer 2002) and co-governance was highlighted as critical for biodiversity conservation in estuaries with high numbers of activities (Kehoe et al. 2021), such as the estuaries within cluster 1 of this analysis. In particular, the incorporation of Indigenous knowledge is an important next step and would improve understanding of the cultural importance, local conditions, and species-habitat associations specific to each estuary. In their assessment of recovery strategies for Pacific salmon populations in the lower Fraser River, Chalifour et al. (2022) identified co-governance between First Nations, provincial, and federal governments to be an important enabling strategy to improve feasibility and potential outcomes of multiple proposed management options. Coordination with the Coastal Marine Strategy that is being developed by the Province of BC with First Nations to identify priorities for nearshore ecosystems along the BC coast may also be an important avenue for developing partnerships related to estuary planning. Draft policy intentions (Province of BC 2022) for the Strategy include monitoring and protecting coastal ecosystems, increasing efforts to sustain wild salmon, and describing the status of estuaries and associated habitats. In addition, several estuaries overlap with areas currently contained within MPAs or are within areas that have been identified for potential spatial protection, so management opportunities available through tools such as MPAs, or the newer Ecologically Significant Areas (ESAs) focused on protection of fish habitats, could be investigated for the activities and stressors identified for individual estuaries. For example, ESAs focus on the long-term protection of highly productive, sensitive, rare, and/or unique fish habitats (DFO 2023a), which is of high relevance for estuaries, particularly those affected adversely by human activities other than fishing.

An additional next step is to facilitate the coordinated collection of finer scale spatial data for fish and fish habitats within estuaries. Researchers point to the need for improved understanding of the species- and population-specific habitat needs for Pacific salmon throughout their life cycle, particularly within estuaries (Weitkamp et al. 2014; Quinn 2018; Chalifour et al. 2019; Flitcroft et

[14] Enhancing Estuary Habitat & Sustaining Coastal Wildlife | Estuary Resilience

al. 2019). For example, Sharpe et al. (2019) highlighted the need to better incorporate species-specific use of defined estuarine habitats to improve environmental impact assessments for local developments. The assumption that activities, stressors, and habitats are uniformly distributed and of equal quality or intensity, or occur with the same frequency, throughout each analysis unit, in this case an estuary polygon, is a limitation highlighted for cumulative effects assessments (Halpern and Fujita 2013) that applies to this work. At a finer scale, habitats within estuaries may be lost due to localized development or may face differing impacts from broad-scale stressors associated with climate change. Fine scale data for all estuarine habitats is needed so changes can be monitored. Data collection could benefit from imaging from remotely piloted aircraft, as were used recently to create high resolution habitat maps of the Cowichan-Koksilah estuary (Douglas et al. 2022) and informed recent assessments of species richness associated with habitat heterogeneity in eelgrass beds (Proudfoot et al. 2023). Further, a variety of prey species and habitat preferences may be important for similar species within an estuary (Sharpe et al. 2019). Increased understanding of species-habitat linkages across space and time can help prioritize conservation and management efforts within estuaries, in particular those facing impacts from multiple activities (Greene et al. 2015; Chalifour et al. 2019; Sharpe et al. 2019), which is true for many of the estuaries in the study.

Additional ecological research within estuaries would also improve our understanding of the habitat needs of many fish species highlighted here are as Ecologically Significant. This includes monitoring ecological and human pressures within estuaries to improve our knowledge of species-stressor interactions; and an increased understanding of spatial and temporal dynamics of habitat use within the estuary. This project estimates intertidal biogenic habitat richness, where data are available, within individual estuaries to provide a cursory assessment of environmental heterogeneity but does not investigate the connectivity of those habitats within the estuary or to habitats in neighbouring marine and freshwater environments. Diverse and connected estuarine habitats may support greater biodiversity and productivity (Weitkamp et al. 2014; Nagelkerken et al. 2015; Chalifour et al. 2019; Seitz et al. 2020) and are important for both estuarine ecosystems and the land-sea interface critical to species such as Pacific salmon (Toft et al. 2018; Sharpe et al. 2019). Heterogeneity across and within habitat types may also influence species abundance and richness (Minello et al. 2003; Proudfoot et al. 2023). While the results of the cluster analysis point to estuaries where high development makes habitat degradation and fragmentation more likely, finer-scale habitat data and improved biophysical information within estuaries are an important next step.

Finally, another key next step is to develop finer scale models to better characterize the flow of stressors across stream networks and into estuaries (e.g., Boyd et al. 2022) and the distribution of stressors and species across estuaries. Given the complex circulation patterns within estuaries resulting from the inflow of freshwater from stream networks and marine water from offshore, finer scale oceanographic models, as well as stream flow dynamics, would be required. This would further understanding of the correlation between land use and flow patterns observed in other areas (Greene et al. 2015), as well as spatial patterns observed across estuaries. For example, Robinson et al. (2011) found species richness varied in eelgrass meadows based on their location within an estuary and Sharpe et al. (2019) linked the distribution of several species within the Skeena estuary with habitat and environmental gradients. Further, the available spatial data for BC’s estuaries could be used to expand previous characterizations of the geomorphology of estuaries along the west coast of North America (Emmett et al. 2000) to further our understanding of the biophysical functioning of individual estuaries and the extent to which morphology influences the structure of estuarine fish communities (Schrandt et al. 2018). This work could build upon indicator work related to Pacific salmon (Stalberg et al. 2009; Pickard et al. 2015), as well as work in the United States, where the condition of estuaries is assessed regularly, and data loggers are used to gather information on physical and chemical variables related to eutrophication, sedimentation, and indicators of fish and human health, including temperature, depth, salinity, dissolved oxygen, turbidity, pH, nitrogen, phosphorous, and chlorophyll[15].

Finer scale species and habitat information could help guide localized studies to investigate the utilization of different estuarine habitats and better understand estuarine habitat mosaics and how different stressors impact the distribution, abundance, diversity, and health of fish and fish habitat within estuaries. Research such as the recent surveys within the Skeena estuary provide important insight into food web dynamics and spatiotemporal variabilities within the estuary that improved upon analyses based solely on habitat information. Differences in distributions of Ecologically Significant fish and invertebrate species were found for a variety of environmental variables (e.g., juvenile Sockeye and Chinook Salmon and Pacific Herring were more abundant in areas of higher temperature, juvenile Sockeye and Coho Salmon were associated with higher turbidity, and calanoid copepod and Surf Smelt abundance was correlated with salinity), habitat and prey distributions (e.g., juvenile Sockeye and harpacticoid copepods were more abundant in eelgrass habitats), locations within the estuaries (e.g., higher abundances of larval Eulachon were caught near the mouth of the river), and temporal considerations (e.g., relative abundances of Surf Smelt decreased over the sampling years while catches of Pacific Herring remained consistent) (Arbeider et al. 2019; Sharpe et al. 2019; Sharpe et al. 2021) Similarly, Seitz et al. (2020) found richness and abundance increased across the salinity gradient in the Central Coast's Koeye estuary (cluster 5) and observed variation in predation risk and productivity among across estuarine habitats and seasons.

This classification of BC estuaries based on anthropogenic activities and identification of estuaries important for significant fish and sensitive fish habitats can help managers begin prioritizing estuaries for management and conservation planning. This broad-scale analysis represents an initial assessment of BC's estuaries that can help guide localized efforts and identify opportunities for collaborations and management efficiencies for estuaries that face similar activities and stressors and can be used in combination with efforts to assess habitat-specific and cumulative impacts within estuaries. This work can continue to be advanced through partnerships focused on the collection and analysis of finer scale information within estuaries to improve our understanding and monitoring of these dynamic ecosystems.

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APPENDIX A. LITERATURE REVIEW ELIGIBILTY FLOW DIAGRAM

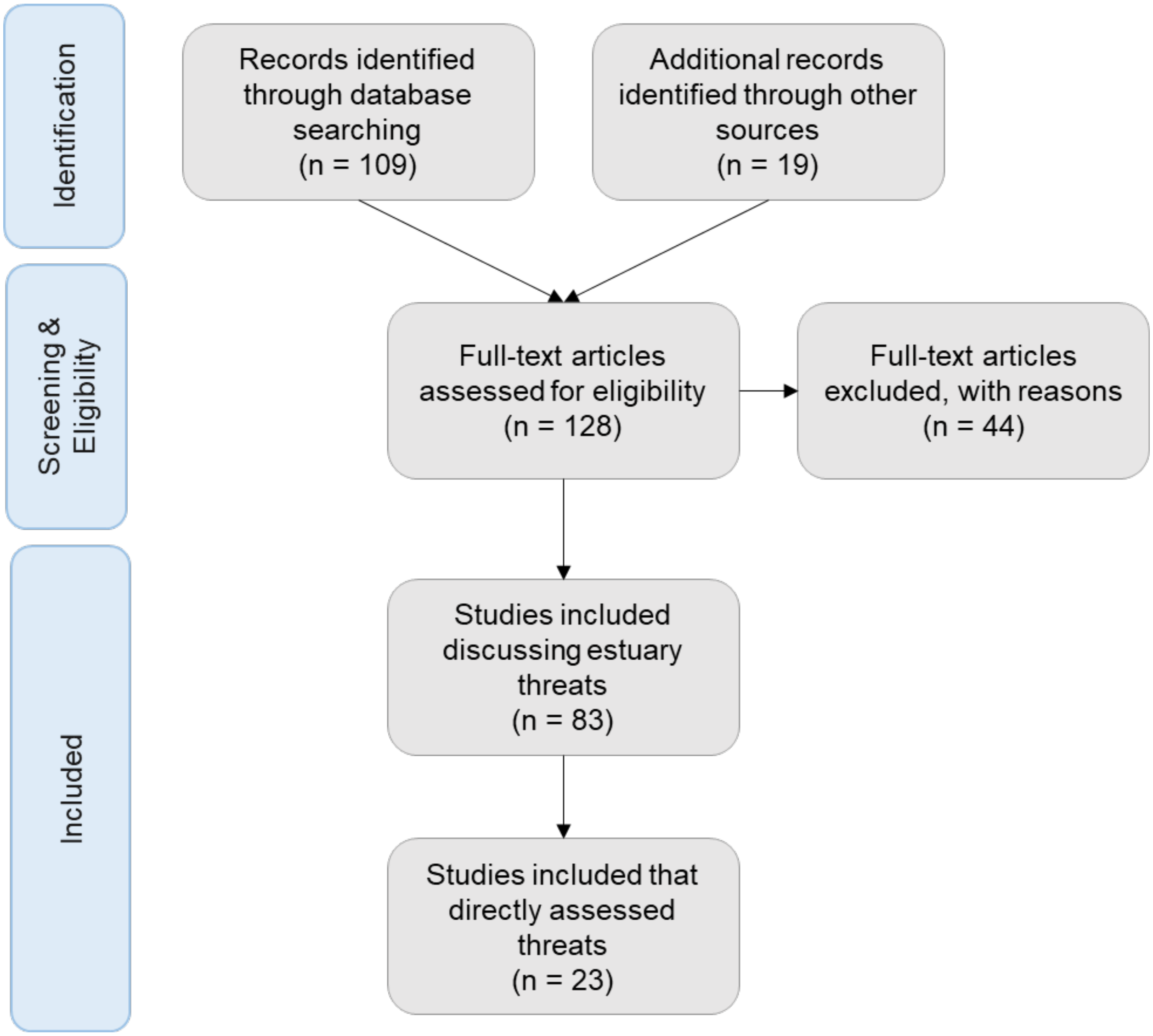

Figure A1. Literature review eligibility flow diagram for final study selection.

APPENDIX B. LITERATURE REVIEW PAPERS

Abbas, A.M., Pickart, A.J., Goldsmith, L.M., Davenport, D.N., Newby, B., Muñoz-Rodríguez, A.F., Grewell, B.J., and Castillo, J.M. 2021. Seed bank persistence of a South American cordgrass in invaded northern Atlantic and Pacific Coast estuaries. AoB Plants 13(3): 1–11.

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APPENDIX C. WATERSHED AREAS

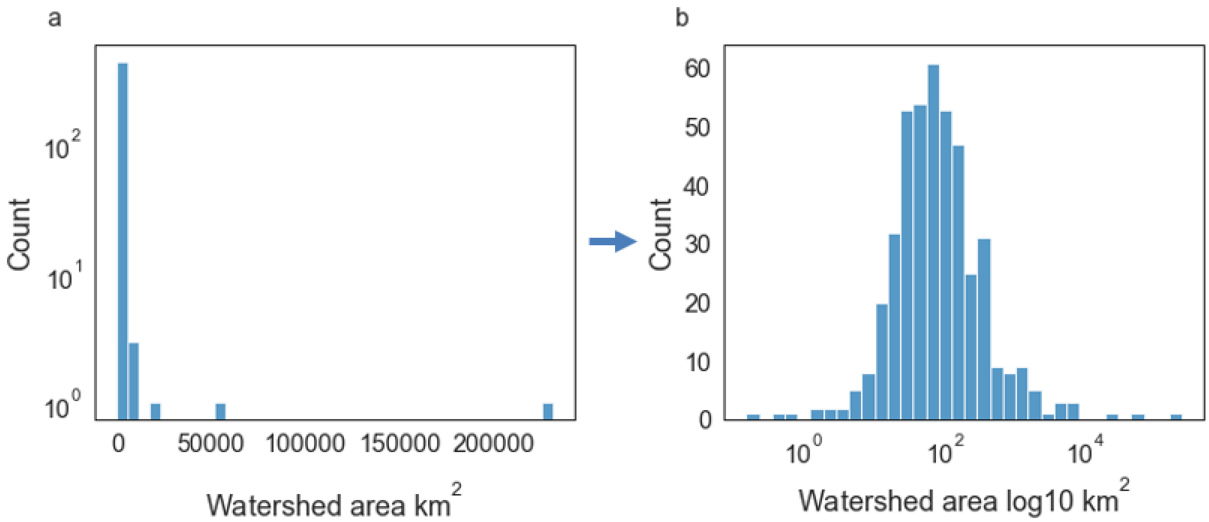

Figure C1. Watershed area distributions: (a) non log transformed, and (b) log transformed to achieve a normal distribution. The y-axis in (a) is log scaled so that bins with one record appear.

APPENDIX D. ESTUARINE SPECIES

Table D1. Estuarine fish species documented in species lists found in BC estuary management plans and associated literature that were not identified as Ecologically Significant in a past assessment (Gale et al. 2019). Species were considered Ecologically Significant if they scored high (2) for any of the ecological roles assessed.

Common Name	Scientific Name	ESS Criteria Score (where assessed)	Campbell River Estuary	Courtenay Estuary	Cowichan -Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary	Skeena Estuary
Arrow Goby	*Clevelandia ios*	-	-	-	-	X	-	-	-	-
Bay Goby	*Lepidogobius lepidus*	-	-	X	-	-	X	X	-	-
Bay Pipefish	*Syngnathus leptorhynchus*	-	-	X	-	X	-	X	-	X
Blackbelly Eelpout	*Lycodes pacifica*	-	-	-	-	X	-	-	-	-
Blackeye Goby	*Rhinogobiops nicholsii*	-	-	X	-	-	-	-	-	-
Buffalo Sculpin	*Enophrys bison*	-	-	X	-	X	-	-	-	-
Butter Sole	*Isopsetta isolepis*	1 (upper-level)	-	-	-	X	-	-	-	-
C-O Sole	*Pleuronichthys coenosus*	-	-	X	-	-	-	-	-	-
Copper Rockfish	*Sebastes caurinus*	1 (upper-level), 1* (forage)	-	X	-	-	-	-	-	X
Crescent Gunnel	*Pholis laeta*	-	-	X	-	X	X	-	-	-
Dover Sole	*Microstomus pacificus*	1 (upper-level)	-	-	-	X	-	-	-	-
English Sole	*Parophrys vetulus*	1 (upper-level)	-	-	-	X	X	X	-	-
Flathead Sole	*Hippoglossoides ellasodon*	-	-	-	-	X	-	-	-	-
Fluffy Sculpin	*Oligocottus snyderi*	-	-	X	-	-	-	-	-	-
Kelp Greenling	*Hexagrammos decagrammus*	-	-	X	-	X	-	-	-	X
Kelp Perch	*Brachyistius frenatus*	1* (forage)	-	X	-	X	X	-	-	-
Kelp Poacher	*Agonomalus mozinoi*	-	-	-	-	X	-	-	-	-
Largescale Sucker	*Catostomus macrocheilus*	-	-	-	-	X	-	-	-	-
Longfin Smelt	*Spirinchus thaleichthys*	1* (forage, nutrient transport)	-	-	-	X	-	-	-	X
Northern Anchovy	*Engraulis mordax*	1* (forage)	-	X	-	X	-	-	-	X
Northern Clingfish	*Gobiesox maeandricus*	-	-	-	-	-	-	-	-	X
Northern Pikeminnow	*Ptychocheilus oregonensis*	-	-	-	-	X	-	-	-	-

Common Name	Scientific Name	ESS Criteria Score (where assessed)	Campbell River Estuary	Courtenay Estuary	Cowichan -Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary	Skeena Estuary
Pacific Hagfish	*Eptatretus stoutii*	-	-	-	-	-	-	-	-	X
Pacific Lamprey	*Entosphenus tridentatus*	-	X	-	-	X	-	X	-	X
Pacific Sanddab	*Citharichthys sordidus*	-	-	-	-	X	-	-	-	-
Pacific Sandfish	*Trichodon tricodon*	1 (forage)	-	X	-	-	-	-	-	X
Pacific Snake Prickleback	*Lumpenus sagitta*	-	-	X	-	-	-	-	-	-
Pacific Spiny Lumpsucker	*Eumicrotremus orbis*	-	-	-	-	-	-	-	-	X
Pacific Tomcod	*Microgadus proximus*	1* (forage)	-	X	-	X	-	-	-	X
Peamouth Chub	*Mylocheilus caurinus*	-	-	-	-	X	-	-	-	-
Penpoint Gunnel	*Apodichthys flavidus*	-	-	-	-	X	X	-	-	-
Pile Perch	*Phanerodon vacca*	1* (forage)	-	X	-	X	-	X	-	-
Plainfin Midshipman	*Porichthys notatus*	-	-	X	-	X	-	-	-	-
Prickly Sculpin	*Cottus asper*	-	-	X	-	X	X	X	X	-
Quillback Rockfish	*Sebastes maliger*	1 (upper-level), 1* (forage)	-	X	-	-	-	-	-	-
Redside Shiner	*Richardsonius balteatus*	-	-	-	-	X	-	-	-	-
Rex Sole	*Glyptocephalus zachirus*	1 (upper-level)	-	-	-	X	-	-	-	-
River Lamprey	*Lampetra ayresi*	-	-	-	-	X	-	-	-	-
Rock Greenling	*Hexagrammos lagocephalus*	-	-	X	-	X	-	-	-	-
Rock Sole	*Lepidopsetta bilineata*	1 (upper-level)	-	-	-	X	-	-	-	-
Saddleback Gunnel	*Pholis ornata*	-	-	X	-	X	-	-	-	-
Sand Sole	*Psettichthys melanostictus*	1 (upper-level)	-	X	-	X	-	-	-	-
Sharpnose Sculpin	*Clinocottus acuticeps*	-	-	-	-	X	-	-	-	-
Silverspotted Sculpin	*Blepsias cirrhosus*	-	-	-	-	X	-	-	-	-
Slender Sole	*Lyopsetta exilis*	-	-	-	-	X	-	-	-	-
Snailfish	*Liparis* sp.	-	-	-	-	X	-	-	-	-
Snake Prickleback	*Lumpenus sagitta*	-	-	X	-	X	X	X	X	X
Soft Sculpin	*Psychrolutes sigalutes*	-	-	-	-	-	-	-	-	X

Common Name	Scientific Name	ESS Criteria Score (where assessed)	Campbell River Estuary	Courtenay Estuary	Cowichan -Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary	Skeena Estuary
Speckled Sanddab	*Citharichthys stigmaeus*	-	-	X	-	X	-	X	-	-
Spotted Ratfish	*Hydrolagus colliei*	-	-	-	-	-	-	X	-	-
Staghorn Sculpin	*Leptocottus armatus*	-	-	X	-	X	X	X	X	-
Starry Flounder	*Platichthys stellatus*	1 (upper-level)	-	X	-	X	X	X	X	X
Striped Surfperch	*Embiotoca lateralis*	1* (forage)	-	X	-	-	X	-	-	-
Sturgeon Poacher	*Podothecus accipenserinus*	-	-	-	-	-	-	-	-	X
Tadpole Sculpin	*Psychrolutes paradoxus*	-	-	-	-	X	-	-	-	-
Tidepool Sculpin	*Oligocottus maculosus*	-	-	-	-	X	-	-	-	-
Tiger Rockfish	*Sebastes nigrocinctus*	1 (upper-level); 1* (forage)	-	-	-	X	-	-	-	-
Threespine Stickleback	*Gasterosteus aculeatus*	-	X	X	-	X	X	X	X	X
Tubesnout	*Aulorhynchus flavidus*	-	-	-	-	X	X	-	-	X
White Seaperch	*Phanerodon furcatus*	-	-	X	-	-	-	-	-	-
White Sturgeon	*Acipenser transmontanus*	-	-	-	-	X	-	X	-	-
Whitespotted Greenling	*Hexagrammos stelleri*	-	-	X	-	X	-	-	-	-

Table D2. Estuarine invertebrate species documented in species lists found in BC estuary management plans and associated literature that were not identified as Ecologically Significant in a past assessment (Gale et al. 2019). While Dungeness Crab were not considered Ecologically Significant, they were included in the assessment given their importance in estuarine ecosystems and their presence is reported in Table 1. Species were considered Ecologically Significant if they scored high (2) for any of the ecological roles assessed.

Species Group	Common Name	Scientific Name	ESS Criteria Score (where assessed)	Campbell River Estuary	Courtenay Estuary	Cowichan-Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary	Skeena Estuary
Polychaetes	Pacific Neapolitan Lugworm	*Abarenicola pacifica*	-	-	-	-	X	-	-	-	-
Polychaetes	Segmented Worm (Ampharetidae Family)	*Amphicteis sp.*	-	-	-	-	-	-	-	X	-
Polychaetes	Segmented Worm (Opheliidae Family)	*Armandia brevis*	-	-	-	X	-	-	-	-	-
Polychaetes	Boring Polychaete	*Boccardia proboscidea*	-	-	-	-	-	X	-	-	-
Polychaetes	Capitellid Worm	*Capitella capitata*	-	-	-	X	-	X	X	-	-
Polychaetes	Tube-Dwelling Polychaete	*Clymenella torquata*	-	-	-	-	X	-	-	-	-

Species Group	Common Name	Scientific Name	ESS Criteria Score (where assessed)	Campbell River Estuary	Courtenay Estuary	Cowichan-Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary	Skeena Estuary
Polychaetes	Segemented Worm (Phyllodocidae Family)	*Eteone longa*	-	-	-	X	-	-	-	-	-
Polychaetes	Segmented Worm (Goniadidae Family)	*Glycinde picta*	-	-	-	X	-	-	-	-	-
Polychaetes	Nereid Worm	*Hediste limnicola*	-	-	-	-	X	-	-	-	-
Polychaetes	Tube-Dwelling Polychaete	*Hobsonia florida*	-	-	-	-	X	X	X	-	-
Polychaetes	Fanworm	*Manayunkia aestuarina*	-	-	-	-	X	X	X	X	-
Polychaetes	Segmented Worm (Capitellidae Family)	*Mediomastus capensis*	-	-	-	-	-	X	-	-	-
Polychaetes	Segmented Worm (Nephtyidae Family)	*Micronephthys cornuta*	-	-	-	X	-	-	-	-	-
Polychaetes	Goddess-Worms	*Nephtys sp.*	-	-	-	X	-	X	-	-	-
Polychaetes	Thread Sludgeworm	*Notomastus tenuis*	-	-	X	-	-	X	-	-	-
Polychaetes	Segmented Worm (Oweniidae Family)	*Owenia fusiformis*	-	-	-	-	-	X	-	-	-
Polychaetes	Segmented Worm (Oweniidae Family)	*Owenia sp.*	-	-	-	X	-	-	-	-	-
Polychaetes	Polychaetes	*Platynereis bicanaliculata*	-	-	-	X	-	-	-	-	-
Polychaetes	Segmented Worm (Spionidae Family)	*Pseudopolydora kempi*	-	-	-	X	-	X	X	-	-
Polychaetes	Segmented Worm (Spionidae Family)	*Pygospio elegans*	-	-	-	X	X	X	-	X	-
Anemones	Buried Green Anemone	*Anthopleura artemisia*	-	-	-	-	-	X	-	-	-
Anemones	Short Plumose Anemone	*Metridium senile*	-	-	X	-	-	-	-	-	-
Anemones	Plumose Anemone	*Metridium sp.*	-	-	-	-	-	-	-	X	-
Hydrozoan	Black Sea Hydrozoan (Sea Plume)	*Obelia longissima*	-	-	X	-	-	-	-	-	-
Barnacles	Rough Barnacle	*Balanus balanus*	-	-	X	-	-	-	-	-	-
Barnacles	Acorn Barnacle	*Balanus glandula*	-	-	X	-	X	X	-	X	-
Barnacles	Little Brown Barnacle	*Chthamalus dalli*	-	-	X	-	-	-	-	-	-
Crabs	Red Rock Crab	*Cancer productus*	1 (upper-level)	-	X	-	-	X	-	X	-
Crabs	Pygmy Rock Crab	*Glebocarcinus oregonensis*	-	-	-	-	-	-	-	X	-
Crabs	Purple Shore Crab	*Hemigrapsus nudus*	-	-	X	-	-	-	-	-	-
Crabs	Green Shore Crab	*Hemigrapsus oregonensis*	-	-	-	-	-	X	X	-	-
Crabs	Northern Kelp Crab	*Pugettia producta*	-	-	X	-	-	-	-	-	-

Species Group	Common Name	Scientific Name	ESS Criteria Score (where assessed)	Campbell River Estuary	Courtenay Estuary	Cowichan-Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary	Skeena Estuary
Cumaceans	Cumacean	*Alamprops quadriplicatus*	-	-	-	X	X	-	-	-	-
Cumaceans	Cumacean	*Cumacea sp.*	-	X	-	-	-	-	-	-	-
Cumaceans	Cumacean	*Cumella (Cumella) vulgaris*	-	-	-	X	X	X	-	-	-
Isopods	Stubby Isopod	*Gnorimosphaeroma oregonense*	-	X	-	-	X	-	-	X	-
Mysids	Mysid Shrimp	*Mysida spp. (Neomysis mercedis)*	-	X	-	X (mysids)	X	-	-	-	-
Shrimp	California Bay Shrimp	*Crangon franciscorum*	-	-	-	X	-	-	-	-	-
Shrimp	Black-Tailed Shrimp	*Crangon nigricauda*	-	-	-	X	-	-	-	-	-
Shrimp	Kelp Humpback Shrimp	*Hippolyte clarki*	-	-	-	X	-	-	-	-	-
Shrimp	Flexed Pink Shrimp	*Pandalus goniurus*	-	-	-	-	-	-	-	X	-
Shrimp	Blue Mud Shrimp	*Upogebia pugettensis*	-	-	X	-	X	X	X	-	-
Tanaids	Tanaid	*Chondrochelia savignyi*	-	-	X	-	-	-	-	-	-
Zooplankton	Amphipods	*Americorophium brevis*	-	-	-	X	-	-	-	-	-
Zooplankton	Amphipods	*Americorophium salmonis*	-	-	-	-	X	X	-	X	-
Zooplankton	Amphipods	*Ampithoe sp.*	-	-	-	X	-	-	-	-	-
Zooplankton	Amphipods	*Anisogammarus pugettensis*	-	X	-	X	X	-	-	-	-
Zooplankton	Amphipods	*Corophium sp.*	-	X	X	X	-	-	-	-	-
Zooplankton	Amphipods	*Crassicorophium crassicorne*	-	-	-	X	-	-	-	-	-
Zooplankton	Amphipods	*Eogammarus confervicolus*	-	X	-	-	X	X (*Eogammarus sp.)*	-	X	-
Zooplankton	Amphipods	*Eogammarus oclairi*	-	-	-	X	-	-	-	-	-
Zooplankton	Amphipods	*Monocorophium insidiosum*	-	-	-	X	-	-	-	-	-
Zooplankton	Amphipods	*Paramoera columbiana*	-	-	-	-	-	X	-	-	-
Zooplankton	Amphipods	*Paramoera sp.*	-	-	-	X	-	-	-	-	-
Sea cucumbers	California Sea Cucumber	*Apostichopus californicus*	-	-	X	-	-	-	-	-	-
Sand dollars	Eccentric Sand Dollar	*Dendraster excentricus*	-	-	X	-	-	-	-	-	-
Sea stars	Leather Star	*Dermasterias imbricata*	-	-	X	-	-	-	-	-	-
Sea stars	Blood Sea Star	*Henricia sanguinolenta*	-	-	X	-	-	-	-	-	-

Species Group	Common Name	Scientific Name	ESS Criteria Score (where assessed)	Campbell River Estuary	Courtenay Estuary	Cowichan-Koksilah Estuary	Fraser Estuary	Nanaimo Estuary	Somass Estuary	Squamish Estuary	Skeena Estuary
Sea stars	Giant Pink Star	*Pisaster brevispinus*	-	-	X	-	-	-	-	-	-
Bivalves	Little Pink Clam	*Macoma balthica*	-	-	-	X	X	X	-	X	-
Bivalves	Bent-Nose Clam	*Macoma nasuta*	-	-	-	-	-	X	X	-	-
Bivalves	Blue Mussel	*Mytilus edulis*	1* (forage, habitat-forming)	-	X	-	-	-	-	-	-
Chitons	Mossy Chiton	*Mopalia muscosa*	-	-	X	-	-	-	-	-	-
Chitons	Lined Chiton	*Tonicella lineata*	-	-	X	-	-	-	-	-	-
Gastropods	Tall-Spired Snail	*Batillaria attramentaria*	-	-	-	-	X	-	-	-	-
Gastropods	Mudflat Snail	*Batillaria sp.*	-	-	-	-	-	X	-	-	-
Gastropods	Zoned Horned Snail	*Batillaria zonalis*	-	-	X	-	-	-	-	-	-
Gastropods	Blister Glassy-Bubble	*Haminoea vesicula*	-	-	X	-	-	-	-	-	-
Gastropods	Fingered Limpet	*Lottia digitalis*	-	-	X	-	-	-	-	-	-
Gastropods	Shield Limpet	*Lottia pelta*	-	-	X	-	-	-	-	-	-
Gastropods	Mask Limpet	*Lottia persona*	-	-	X	-	-	-	-	-	-
Gastropods	Lean Western Nassa	*Nassarius mendicus*	-	-	-	-	X	-	-	-	-
Gastropods	Lewis' Moon Snail	*Neverita lewisii*	-	-	X	-	-	X	-	-	-
Gastropods	Frilled Dogwinkle	*Nucella lamellosa*	-	-	X	-	-	-	-	-	-
Nudibranchs	Leopard Dorid	*Diaulula sandiegensis*	-	-	X	-	-	-	-	-	-
Nudibranchs	Opalescent Nudibranch	*Hermissenda crassicornis*	-	-	-	-	-	-	-	X	-
Nudibranchs	Red Sponge Nudibranch	*Rostanga pulchra*	-	-	X	-	-	-	-	-	-
Horseshoe Worms	Large Green Phoronid	*Phoronopsis harmeri*	-	-	-	-	-	X	-	-	-

APPENDIX E. ECOLOGICAL METRIC DATA SOURCES

Table E1. Data sources for ecological metrics.

Category	Metric	Data Source	Date
Fish	Salmon biomass	NuSEDS-New Salmon Escapement Database System	1920–2021
	Salmon species richness	NuSEDS-New Salmon Escapement Database System	1920–2021
	Salmon Conservation Units	Pacific Salmon Conservation Units, Sites & Status	1920–2021
	Eulachon	Marine Planning Partnership - SeaSketch	2006–2016
	Herring spawn biomass	Pacific Herring spawn index - Fisheries and Oceans Canada	1988–2022
	Pacific Sand Lance	Robinson et al. (2021)	2021
		Huard et al. (2022)	2022
Invertebrates	Dungeness Crab	Nephin et al. (2023)	2023
	Spot Prawn	Fisheries and Oceans Canada – Shellfish Data Unit	1980–2022
Habitat	Eelgrass	Shorezone - Coastal and Ocean Resources	1991–2021
		Fisheries and Oceans Canada	2021
	Saltmarsh	Shorezone - Coastal and Ocean Resources	1991–2021
	Kelp - canopy	Shorezone - Coastal and Ocean Resources	1991–2021
		BC Marine Conservation Atlas - Bull and Giant Kelp Polygons	2010
	Kelp - understory (brown)	Shorezone - Coastal and Ocean Resources	1991–2021
	Green macroalgae	Shorezone - Coastal and Ocean Resources	1991–2021
Substrate	Rock	Fisheries and Oceans Canada - Fields et al. (2020)	2020
	Mixed		
	Sand		
	Mud		
Benthic properties	Rugosity	Fisheries and Oceans Canada - Gregr et al. (2021)	2019
Birds	Estuary importance ranking for waterbirds	Pacific Birds Habitat Joint Venture	2019

APPENDIX F. COMPARISON OF HUMAN ACTIVITIES AND CLUSTER ANALYSIS RESULTS

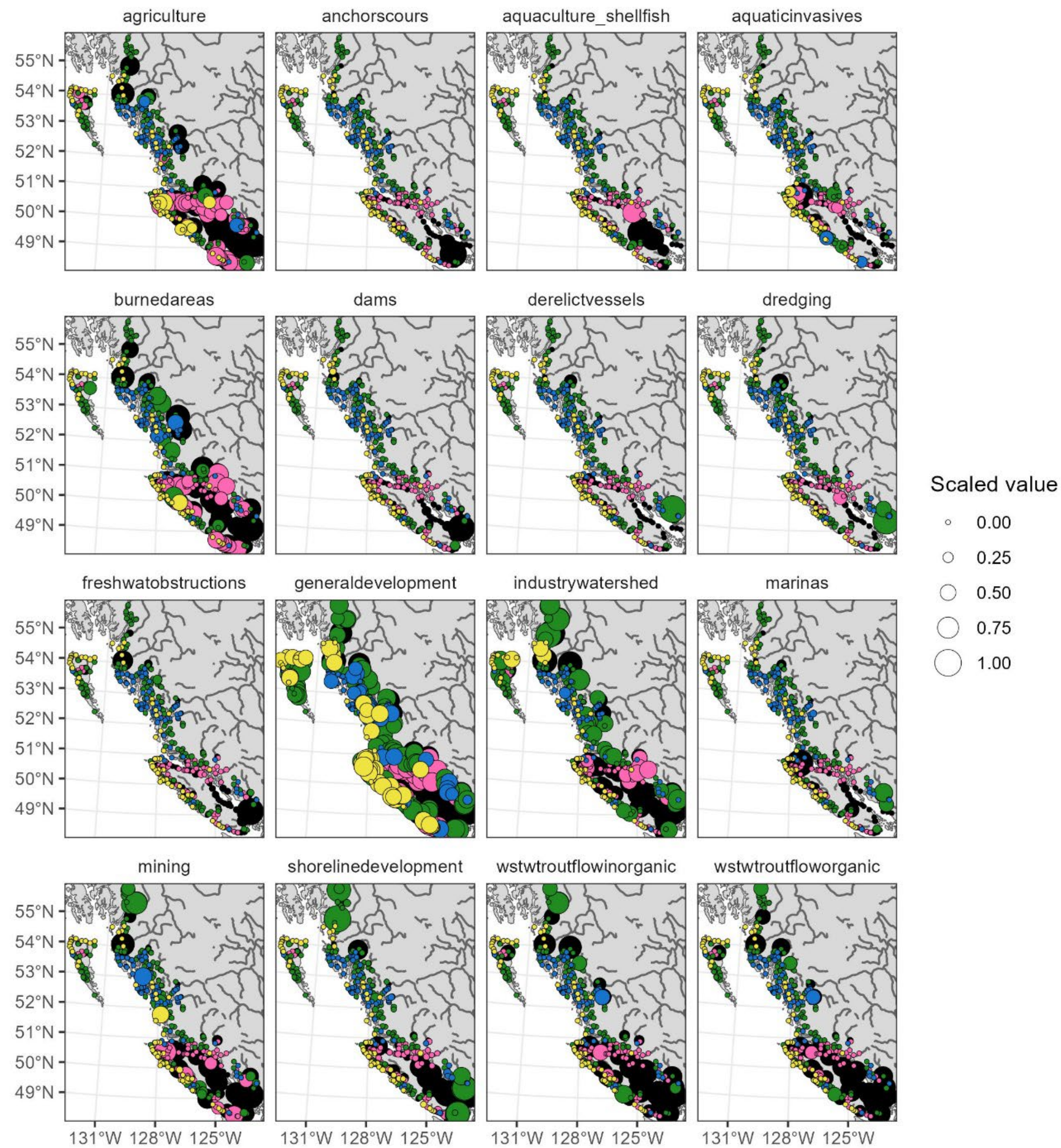

Figure F1. Map of human activities that are significantly associated with cluster 1 (black). The activity names are labelled above the individual panels. The size of the points shows the relative value of the activity. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

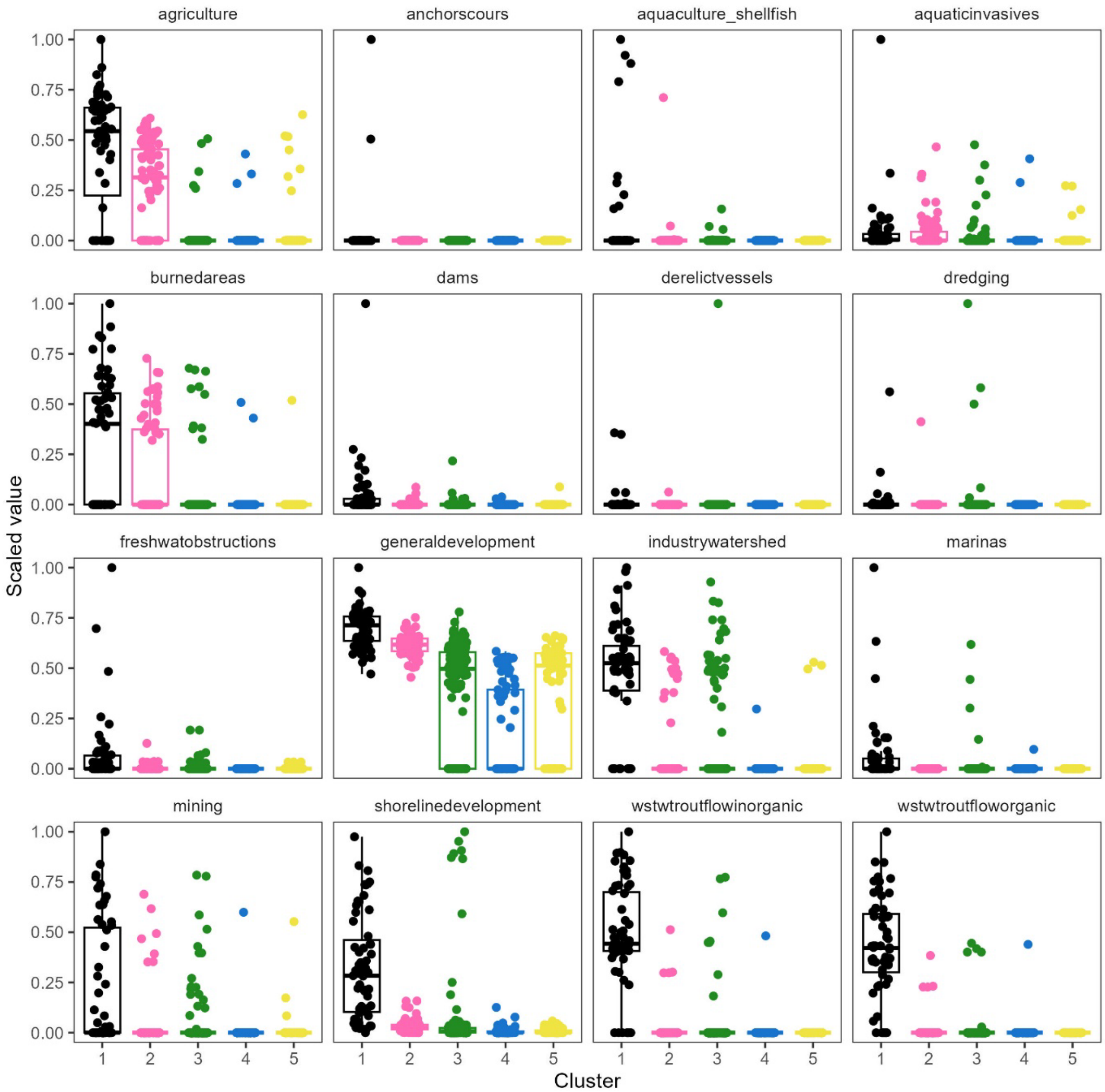

Figure F2. Distribution of values across estuaries in each cluster for activities that are significantly associated with cluster 1. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

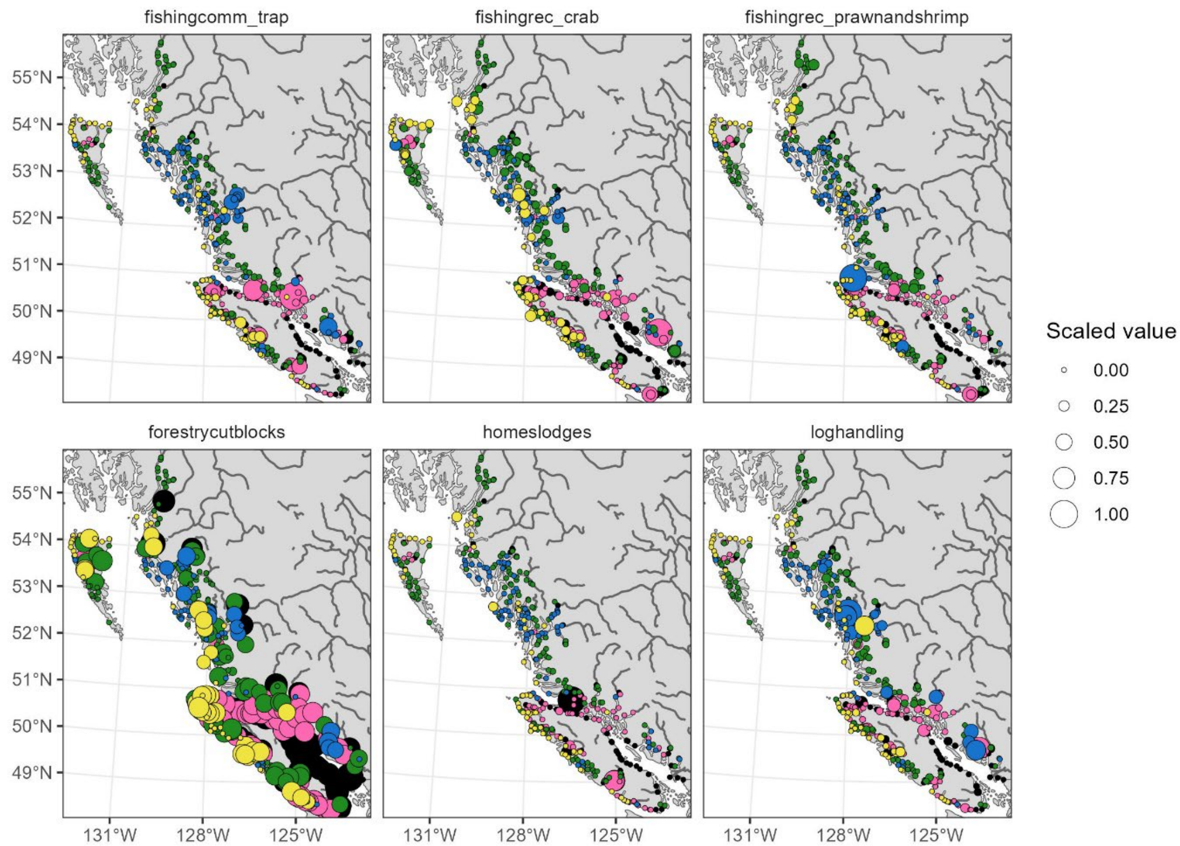

Figure F3. Map of human activities that are significantly associated with cluster 2 (pink). The activity names are labelled above the individual panels. The size of the points shows the relative value of the activity. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

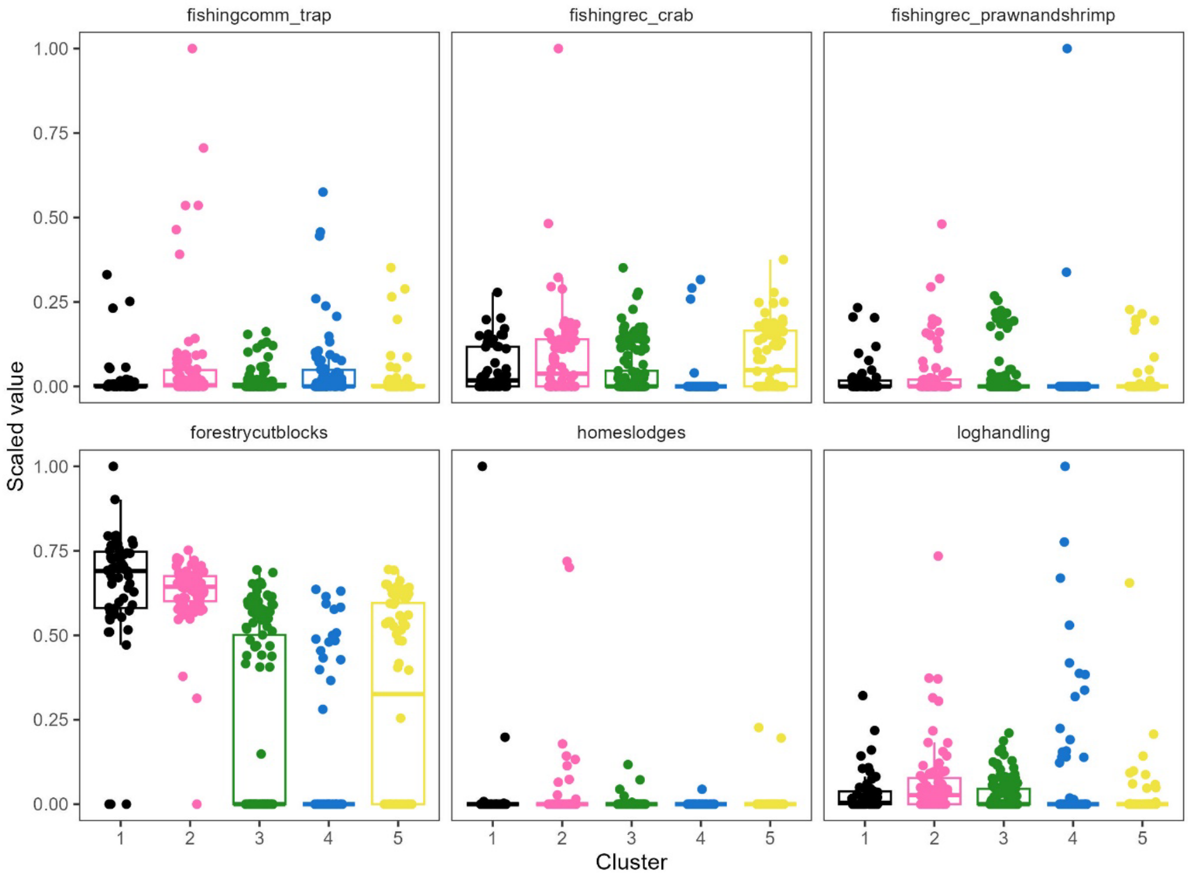

Figure F4. Distribution of values across estuaries in each cluster for activities that are significantly associated with cluster 2. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

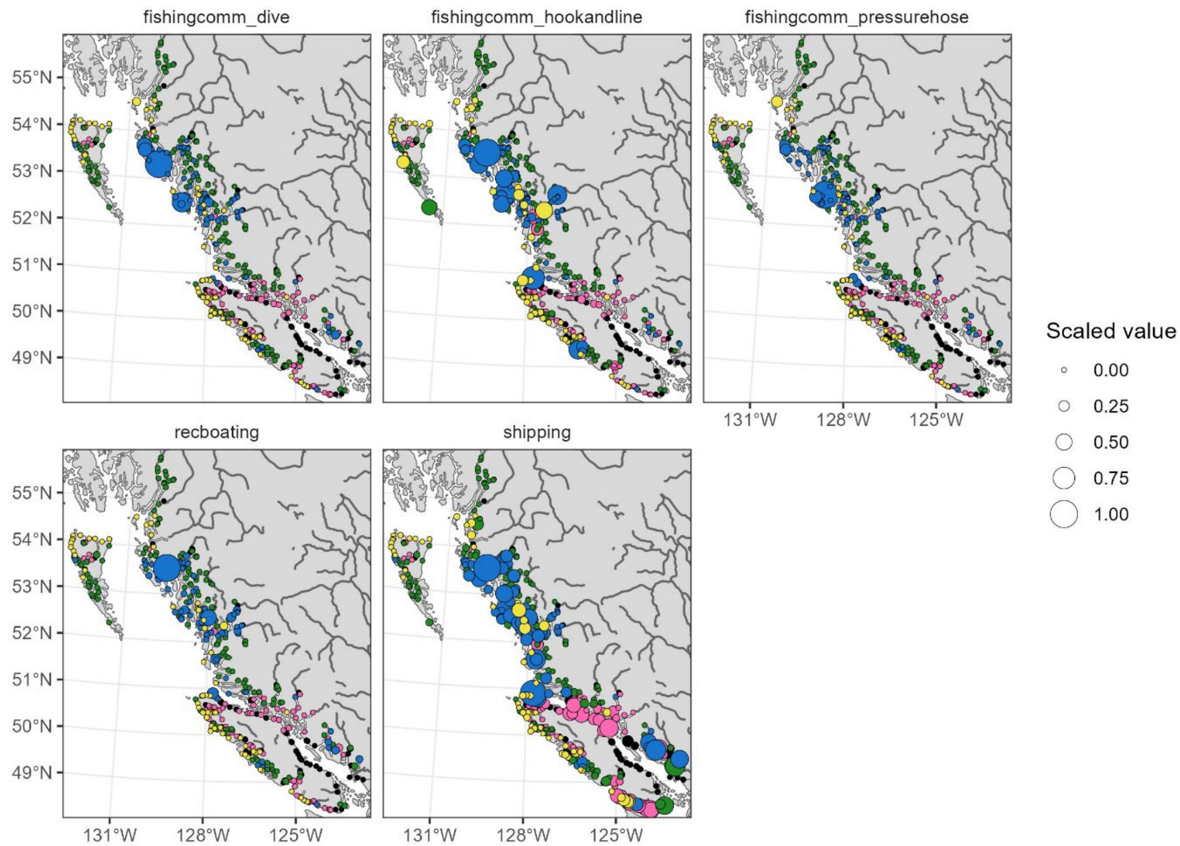

Figure F5. Map of human activities that are significantly associated with cluster 4 (blue). The activity names are labelled above the individual panels. The size of the points shows the relative value of the activity. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

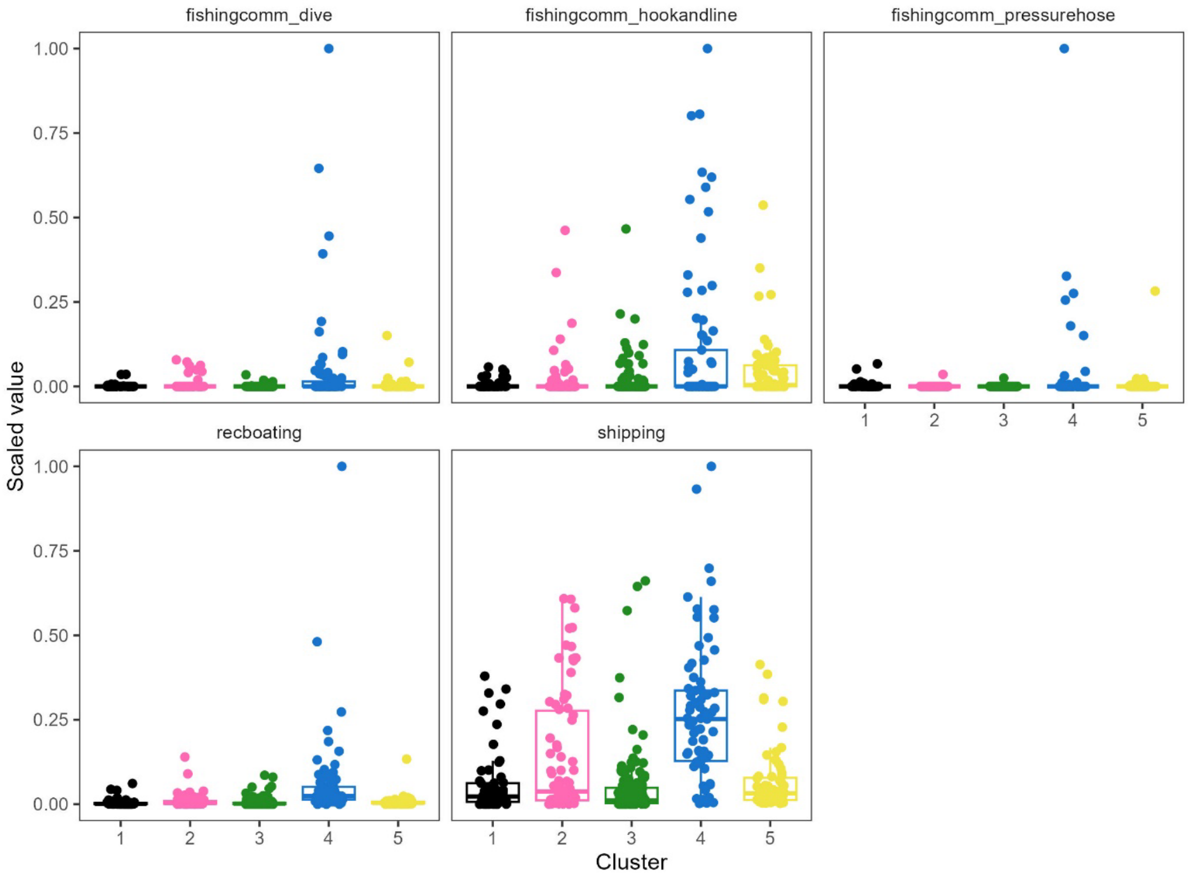

Figure F6. Distribution of values across estuaries in each cluster for activities that are significantly associated with cluster 4. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

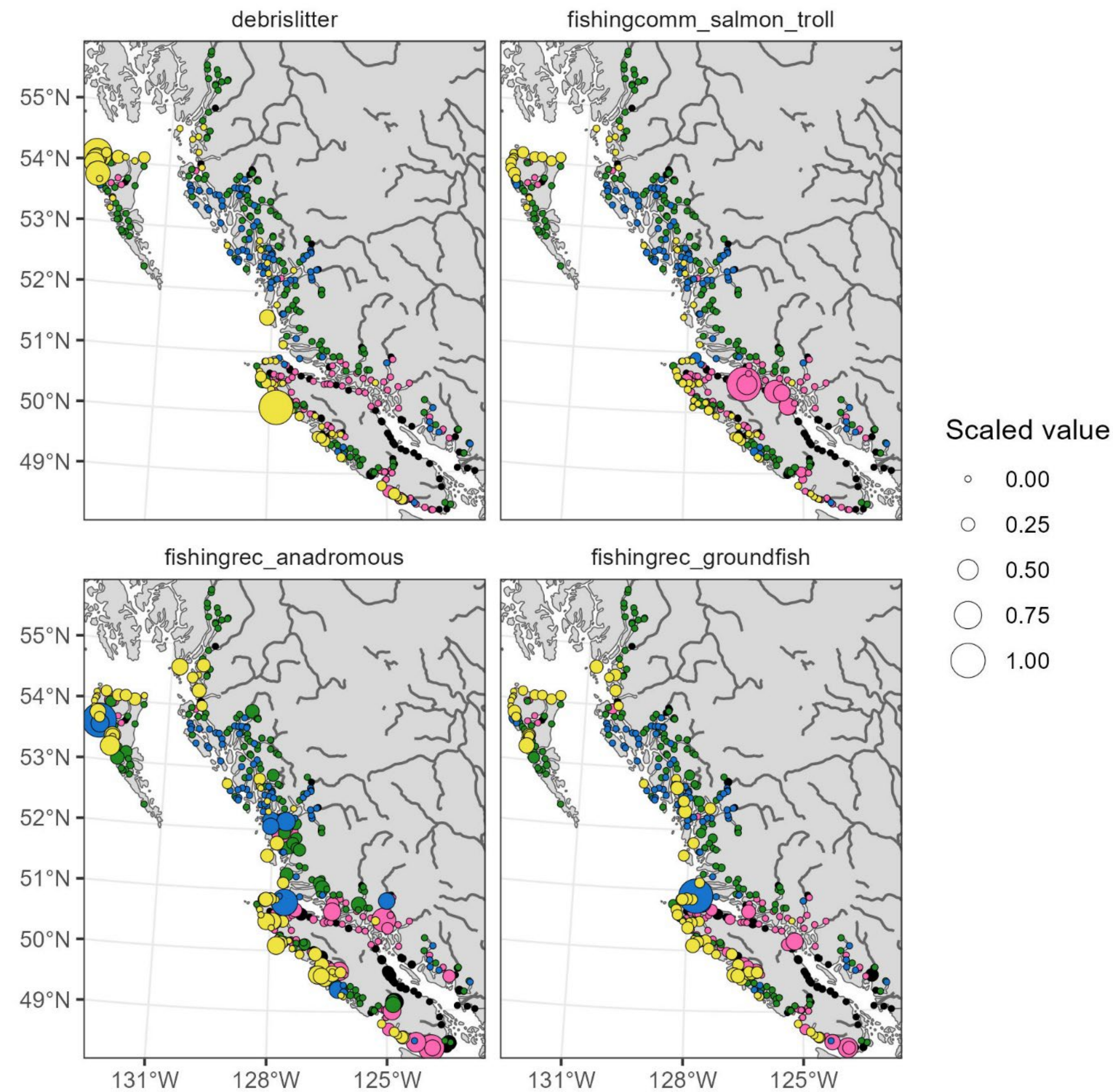

Figure F7. Map of human activities that are significantly associated with cluster 5 (yellow). The activity names are labelled above the individual panels. The size of the points shows the relative value of the activity. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

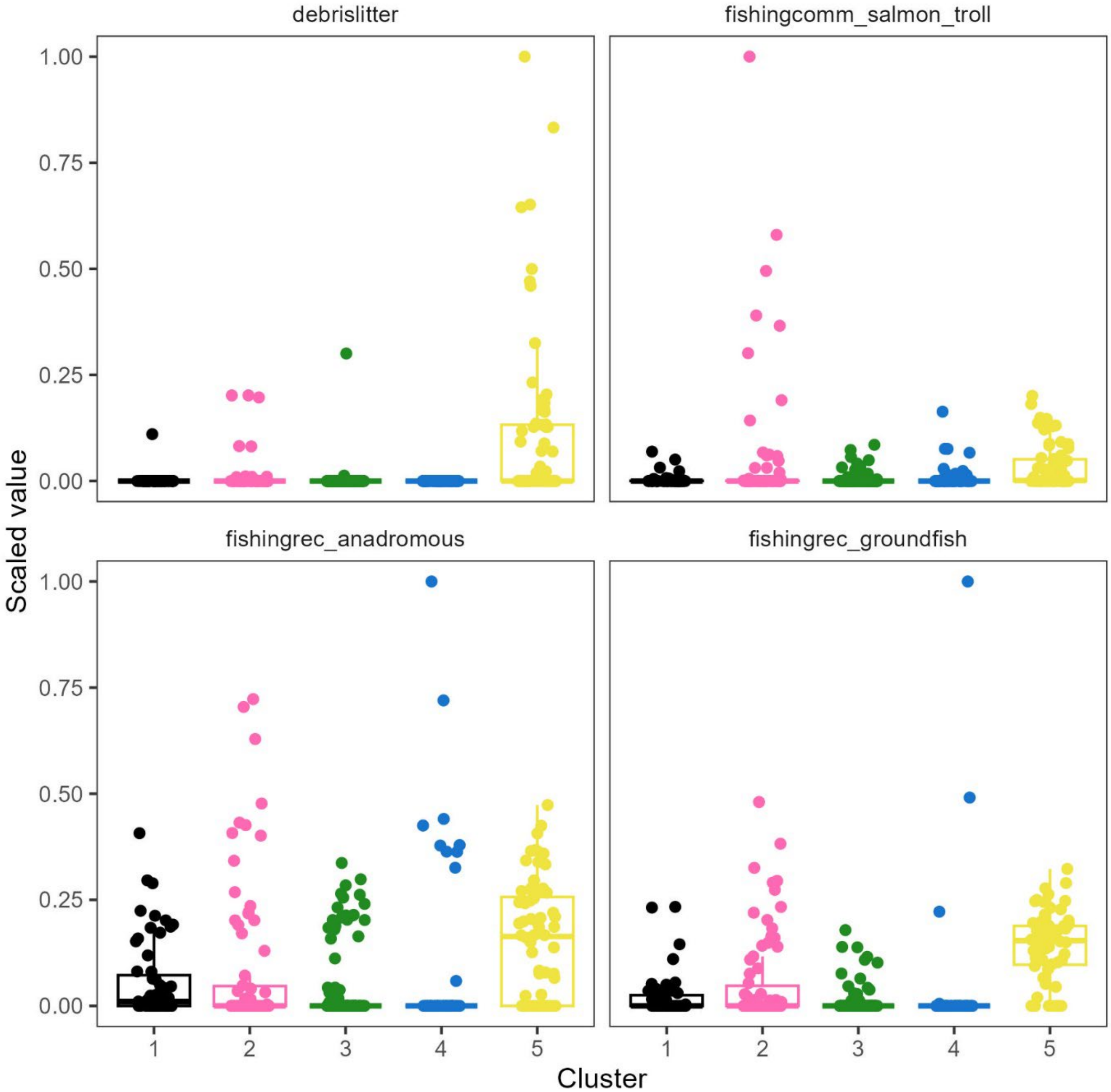

Figure F8. Distribution of values across estuaries in each cluster for activities that are significantly associated with cluster 5. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

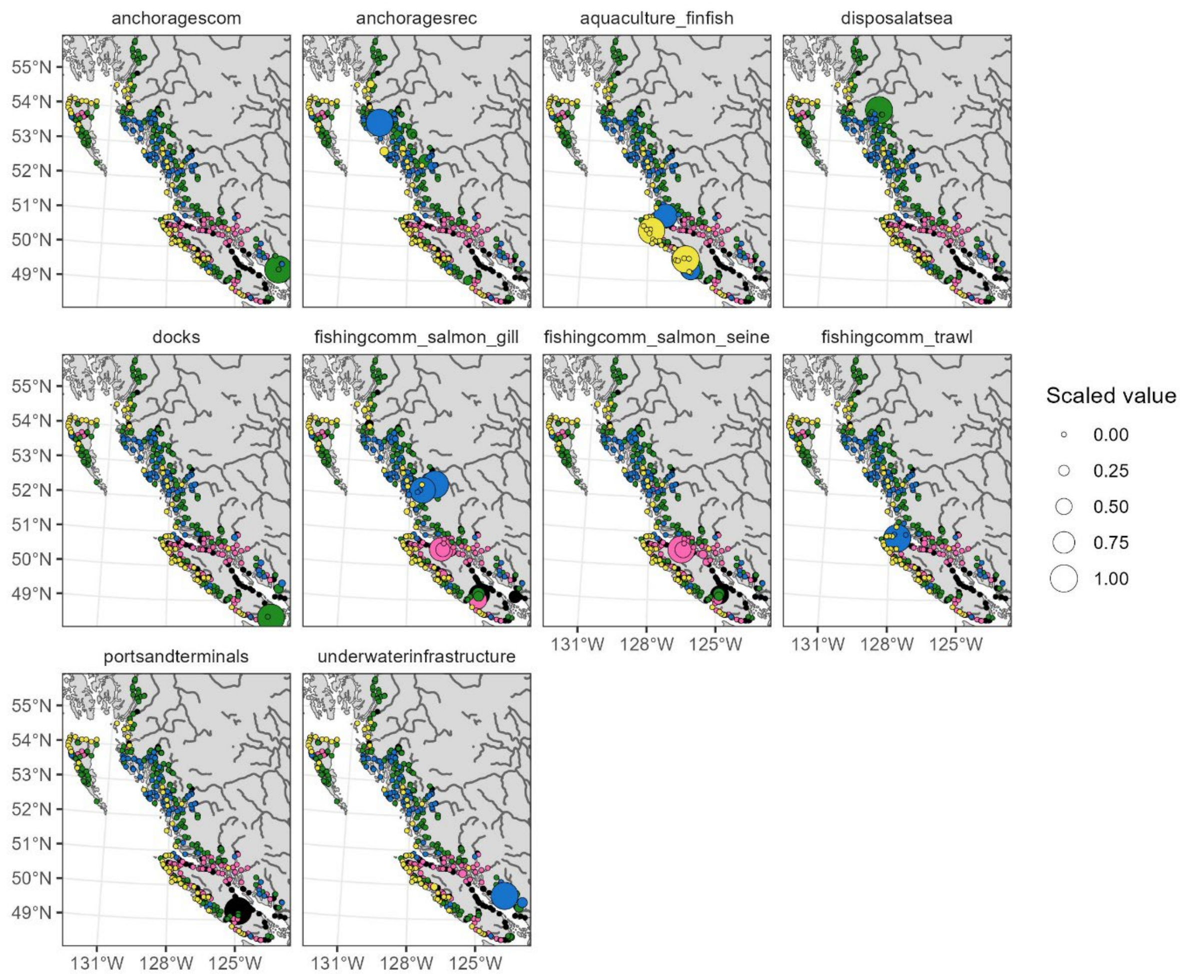

Figure F9. Map of human activities that are not significantly associated with any cluster. The activity names are labelled above the individual panels. The size of the points shows the relative value of the activity. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

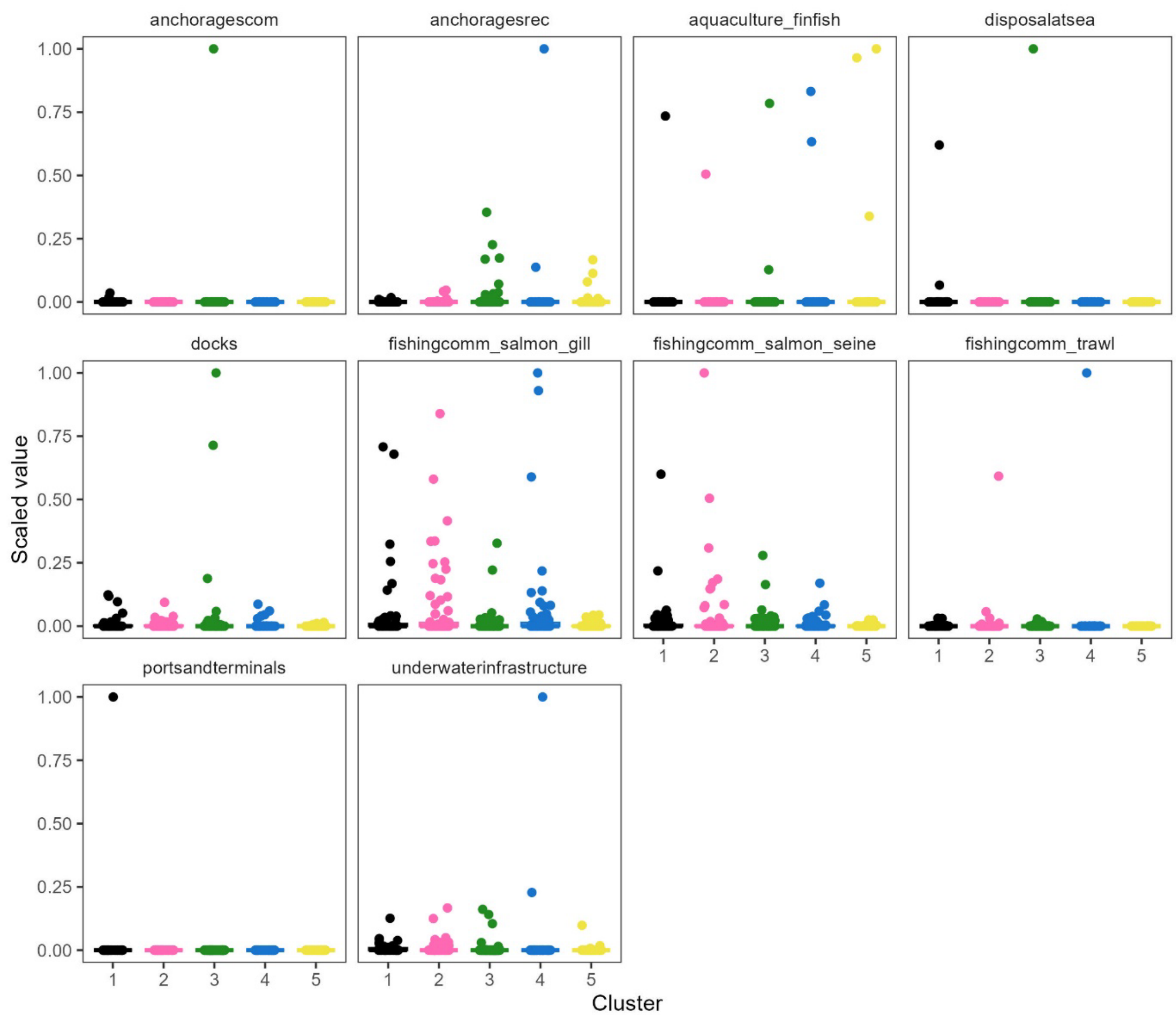

Figure F10. Distribution of values across estuaries in each cluster for activities that are not significantly associated with any cluster. All values have been scaled between their highest and lowest values to facilitate comparison across activities.

APPENDIX G. ACTIVITY AND ECOLOGICAL RESULTS BY ESTUARY

Table G1. Activity data by estuary including cluster assignment, coordinates of estuary centroid, bioregion, estuary and watershed areas, and activity count. Activities marked with an asterisk (*) are restricted datasets and the column is left blank. Area based activities were quantified using a generic raster cell constant value, and the extent of some activities were quantified by buffering and applying a distance decay to the raster values resulting in "generic area units" of overlap with estuaries. Refer to data dictionary (Table G4) for column descriptions and units

(see Coastwide Evaluation and Classification of Pacific Region Estuaries based on Anthropogenic Activities and Significant Fish Habitat - Activity data by estuary)

Table G2. The count and percent of estuaries in which each activity is present. Activities are ordered by percent of estuaries.

Zone	Activity	Dataset name	Estuary count	Percent of estuaries
Marine	Ports and terminals	portsandterminals	1	0.23
Marine	Anchor scours	anchorscours	2	0.46
Marine	Disposal at sea	disposalatsea	3	0.68
Marine	Anchorages – commercial	anchoragescom	4	0.91
Marine	Aquaculture – finfish	aquaculture_finfish	9	2.05
Marine	Derelict vessels	derelictvessels	12	2.73
Marine	Dredging	dredging	17	3.87
Marine	Aquaculture – shellfish	aquaculture_shellfish	17	3.87
Marine	Floating homes and lodges	homeslodges	23	5.24
Marine	Commercial fishing – trawl	fishingcomm_trawl	23	5.24
Marine	Commercial fishing – pressure hose	fishingcomm_pressurehose	30	6.83
Terrestrial	Dams	dams	31	7.06
Marine	Anchorages – recreational	anchoragesrec	32	7.29
Marine	Marinas	marinas	33	7.52
Terrestrial	Debris and litter	debrislitter	42	9.57
Marine	Underwater infrastructure	underwaterinfrastructure	47	10.71
Terrestrial	Freshwater obstructions	freshwatobstructions	48	10.93
Marine	Commercial fishing – dive	fishingcomm_dive	52	11.85
Terrestrial	Mining	mining	57	12.98
Terrestrial	Wastewater outflow – organic	wstwtroutfloworganic	63	14.35
Terrestrial	Wastewater outflow - inorganic	wstwtroutflowinorganic	65	14.81
Terrestrial	Burned areas	burnedareas	69	15.72
Marine	Aquatic invasive species	aquaticinvasives	78	17.77
Marine	Docks	docks	83	18.91
Marine	Recreational fishing – prawn/shrimp	fishingrec_prawnandshrimp	91	20.73
Terrestrial	Industry in watershed	industrywatershed	99	22.55
Terrestrial	Agriculture	agriculture	112	25.51
Marine	Commercial fishing – salmon troll	fishingcomm_salmon_troll	116	26.42
Marine	Commercial fishing – salmon seine	fishingcomm_salmon_seine	120	27.33
Marine	Commercial fishing – hook and line	fishingcomm_hookandline	122	27.79
Marine	Recreational fishing – groundfish	fishingrec_groundfish	130	29.61
Marine	Commercial fishing – salmon gillnet	fishingcomm_salmon_gill	140	31.89
Marine	Recreation fishing – anadromous	fishingrec_anadromous	145	33.03
Marine	Log handling	loghandling	175	39.86
Marine	Recreational fishing – crab	fishingrec_crab	184	41.91
Marine	Commercial fishing – trap	fishingcomm_trap	213	48.52
Terrestrial	Forestry cutblocks	forestrycutblocks	236	53.76
Terrestrial	Shoreline development	shorelinedevelopment	287	65.38
Terrestrial	General development in watershed	generaldevelopment	319	72.67
Marine	Recreational boating	recboating	423	96.36
Marine	Shipping	shipping	439	100

Table G3. Ecological data by estuary including cluster assignment, coordinates of estuary centroid, and bioregion. See Section 3.4 (Fish and Fish Habitat Evaluation) for details on how each metric was calculated. Refer to data dictionary (Table G4) for column descriptions and units.

(see Coastwide Evaluation and Classification of Pacific Region Estuaries based on Anthropogenic Activities and Significant Fish Habitat - Ecological data by estuary)

Table G4. Data dictionary in English and French describing units for fields in Table G1, Table G3, Figure 6, Figure 8.

(see Coastwide Evaluation and Classification of Pacific Region Estuaries based on Anthropogenic Activities and Significant Fish Habitat - Data Dictionary French)

APPENDIX H. MAPS OF ECOLOGICAL RESULTS BY ESTUARY

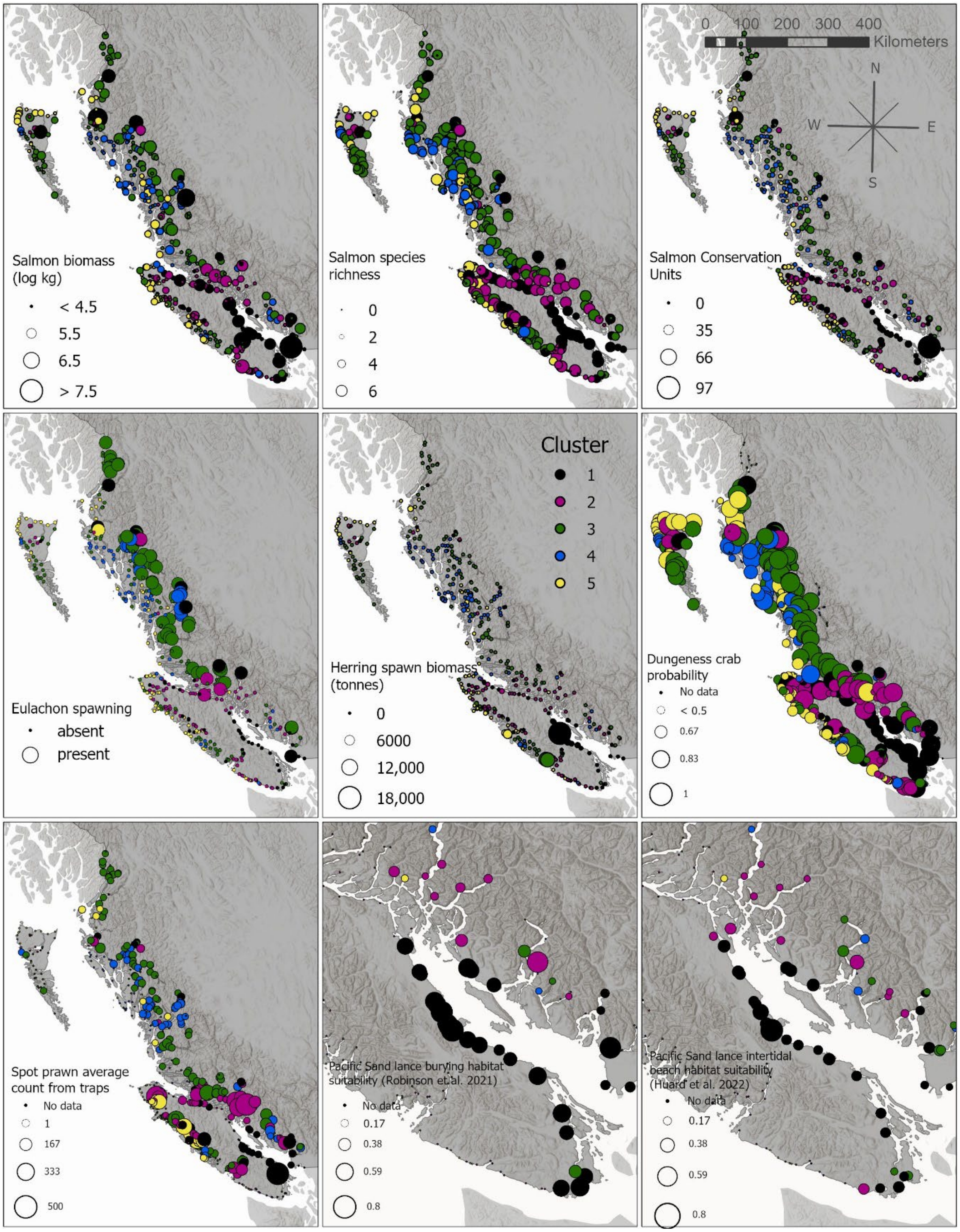

Figure H1. Maps of fish and invertebrates ecological data by estuary. Salmon biomass is symbolized by size on a log scale to visualize more of the variation present in the data.

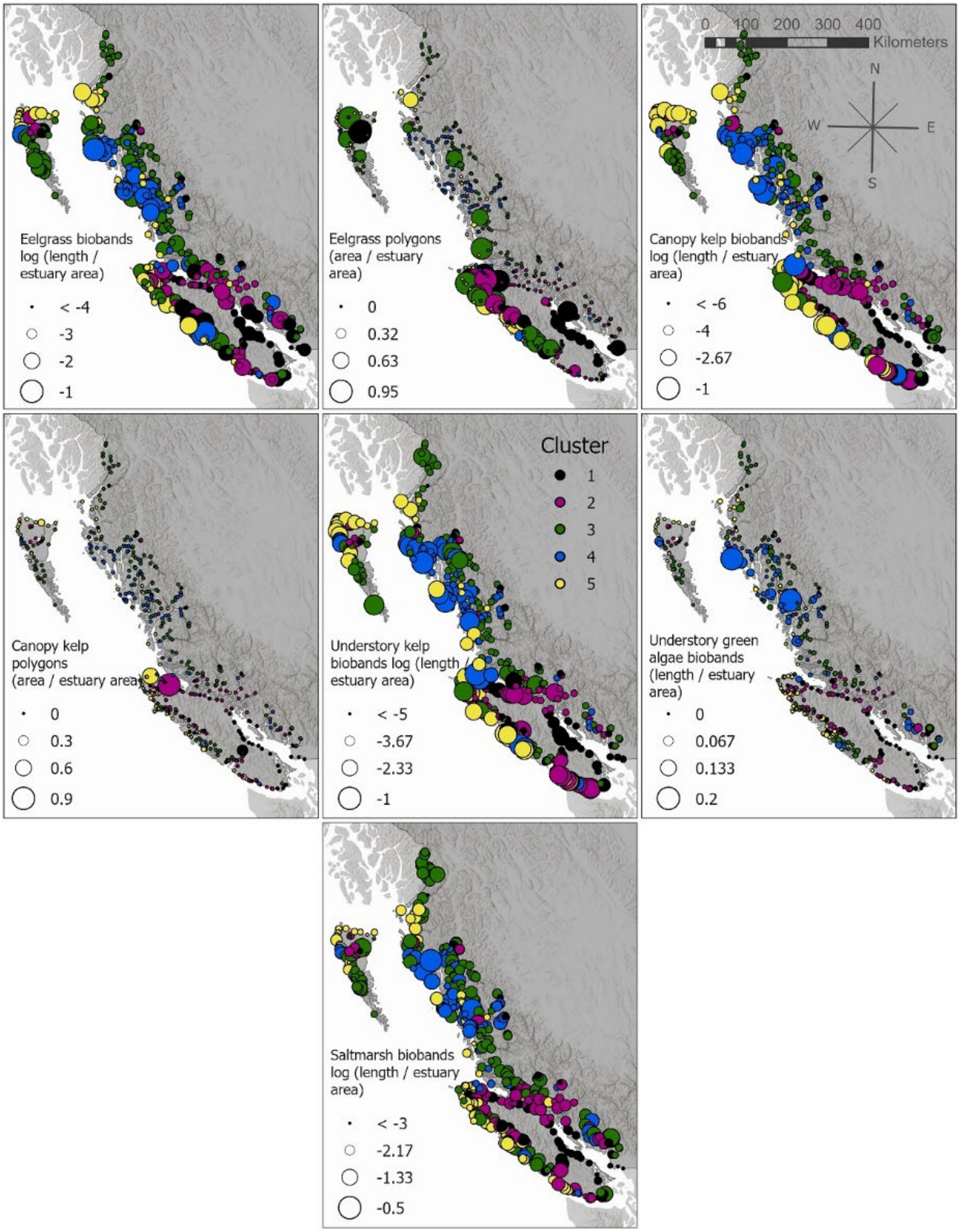

Figure H2. Maps of biogenic habitat types by estuary. The biobands for eelgrass, canopy kelp, understory kelp and saltmarsh are symbolized by size on a log scale to visualize more of the variation present in the data.

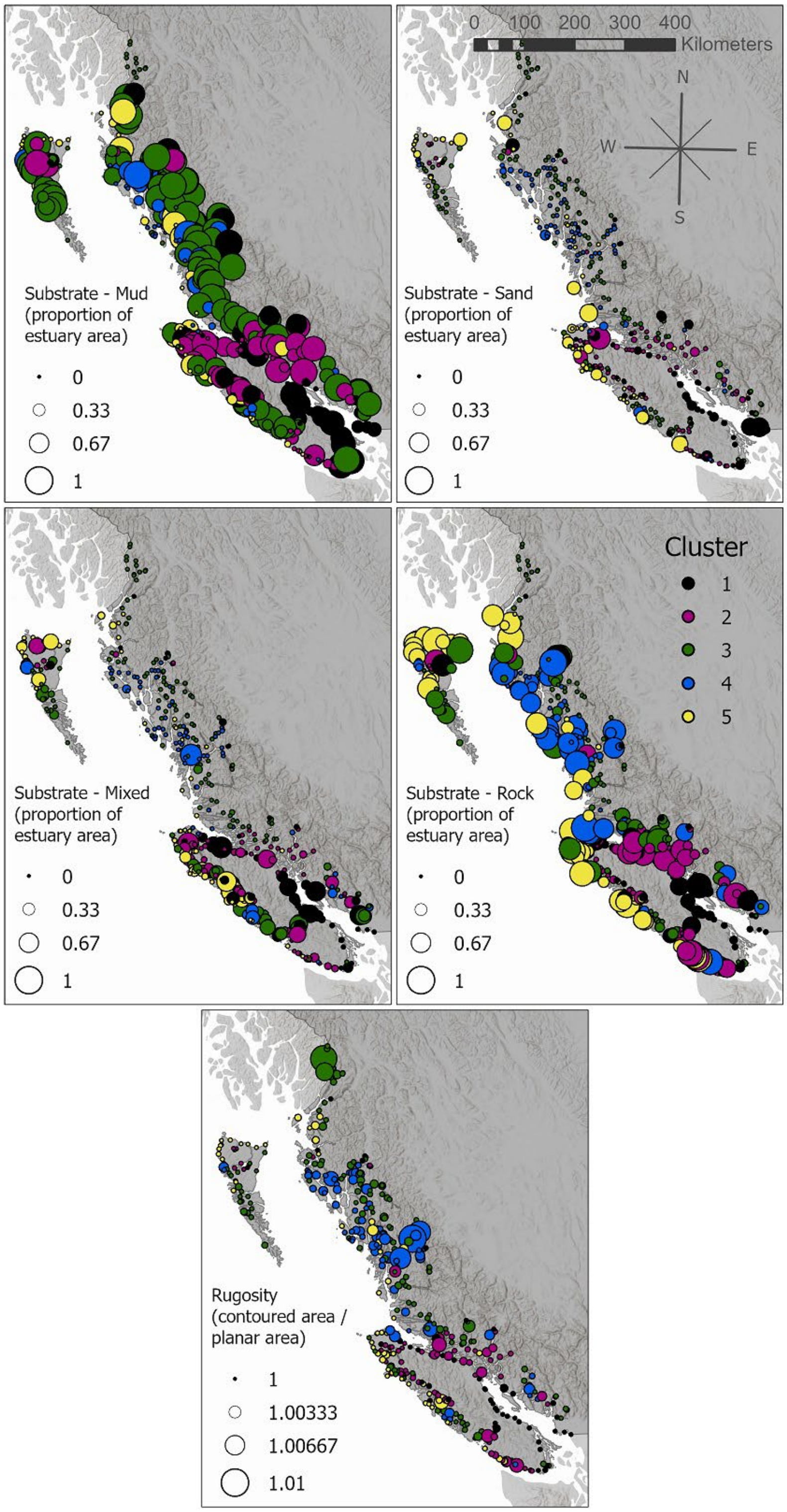

Figure H3. Maps of physical characteristics values by estuary.

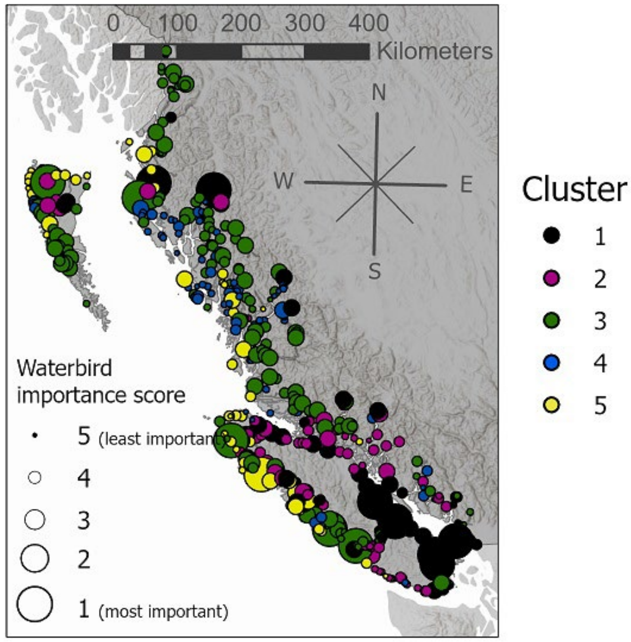

Figure H4. Maps of waterbird importance scores per estuary.