How can we manage toward more resilient landscapes? Assessing how riparian areas could help wildlife move through anthropogenic matrices

by

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Abstract

Landscapes are lessening their ability to support wildlife because of threats from climate change and anthropogenic development. As a result, managers must focus on promoting landscape resilience to maintain all major biotic functional groups. The goal of this research was to explore the potential for riparian areas to serve as a component in landscape-wide management plans to promote resilience. I performed a literature review which discussed the utility of riparian areas by wildlife. I addressed how land use change and climate change could shape how wildlife use riparian areas. I also performed an empirical study of the effects of development intensity and stream channel morphology on mammalian use of riparian areas. I determined that riparian areas are valuable as habitat for wildlife and are important contributors towards landscape resilience. I suggest that management towards landscape resilience requires consideration at both the local habitat patch and broader landscape scales.

Keywords: riparian areas; landscape resilience; camera trapping; habitat use modeling

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Lastly, I would like to express gratitude to the animals who I photographed these past two years. Of course, if they didn't walk in front of my cameras, I would have had

no data, but seeing them interact with each other and their environment was an important reminder of why I pursue ecology. So, I’m thankful for the opportunity to be reconnected with my natural surroundings.

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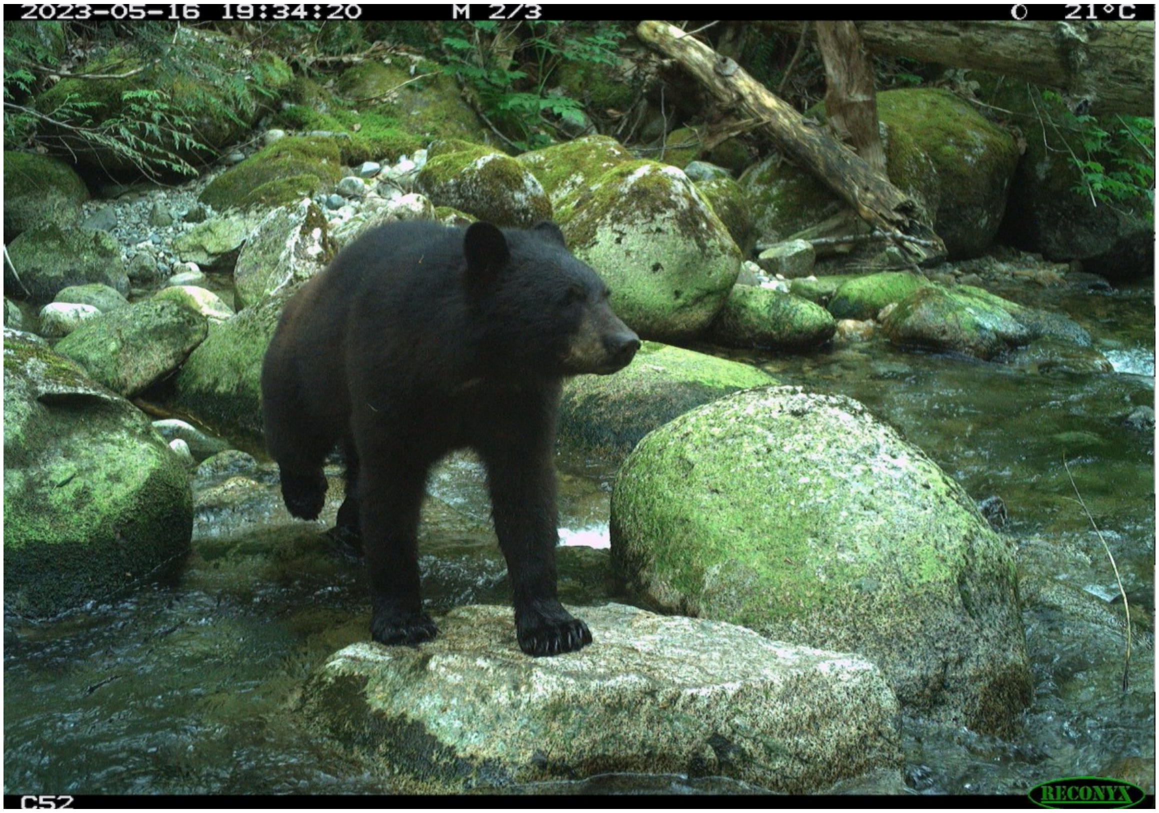
Glossary

Dendritic Network	A spatial pattern of natural habitat patches that stretches continuously throughout a landscape, with branches forking from mainstems like a tree (Campbell Grant et al., 2007); the physical structure of watersheds, and by extension their riparian areas, are examples of dendritic networks.
Ecological Integrity	A measure of how the structure, biotic composition, and functional roles contribute to the overall ecosystem functioning (Ordóñez & Duinker, 2012).
Ecosystem Resilience	The ability for an ecosystem to exist in multiple stability domains (Holling, 1973); or to maintain all its major biotic functional groups (Sundstrom et al., 2012) after a disturbance.
Ecotone	A transition habitat type found at the intersection of two distinct habitat types that contains characteristics of both distinct habitat types (Kark, 2007).
Edge-seeking Species	Species that prefer open, exposed habitat patches typically found along the edges of undistrubed and disturbed habitat patches or at the intersection of two habitat types.
Forest Interior Species	Species that prefer interior parts of the forest that are far from human development and exposed habitat patches.
Functional Groups	Groups of species that perform a similar function (Rosenfeld, 2002).
Functional Redundancy	several species exhibiting the same functional role within a habitat patch or landscape such that if one species is lost, the overall function is not compromised (Biggs et al., 2020).
Habitat	The combination of all resources (i.e., food, water, and space) and environmental conditions (both abiotic conditions and biotic interactions) required to host a given species or population and allow for survival and reproduction (Morrison et al., 2012).
Habitat Complexity	Variation in the physical structure, diversity of niches, and functional roles within a habitat patch (Loke & Chisholm, 2022).
Habitat Fragmentation	Once continuous natural habitat divided by impermeable structures, typically anthropogenic developments or natural barriers (Fahrig, 2003).

Habitat Patch	A singular unit of a habitat, which may not necessarily encompass all the resources and environmental conditions required for a species.
Habitat Type	The vegetation associated with a particular area or the potential of vegetation associations at various successional stages (Daubenmire, 1968).
Hydrologic Regime	The annual patterns of flow within a river or stream.
Home Range	The territory in which an individual will travel while foraging, mating, and raising offspring (Burt, 1943).
Landscape	An entity shaped by the interactions of biota and abiotic factors on Earth's surface, whose extent is species-specific, such that the size of the landscape would encompass all the resources and environmental conditions to host a given species or population and allow for survival and reproduction (Morrison et al., 2012; Zonneveld, 1989); the collection of habitat patches used by a given species or population.
Lowland Habitat	Habitat found at lower elevations, typically near larger and slower-flowing rivers.
Matrix Adaptable Species	Individuals that may not normally select the matrix habitat type but can survive with minimal added stress in developed habitat (Alberti, 2005).
Matrix Avoidant Species	Individuals that cannot survive in the matrix habitat type or in close proximity to humans (Alberti, 2005).
Matrix Habitat Type	Any terrestrial habitat patches adjacent to a riparian area.
Suitable Habitat	Habitat that contains the necessary resources for an organism to survive.
Matrix Tolerant Species	Individuals that may prefer the highly developed matrix habitat type (Alberti, 2005).
Riparian Zone/Area	An ecotone that links aquatic and terrestrial habitat types; the habitat patch from the edge of the streambank to the beginnings of the matrix habitat type (Pedraza et al., 2021).
Wildlife Corridor	A conservation technique designed to facilitate wildlife movement to suitable habitat via continuous natural pathways or stepping-stone pathways of linked natural habitat patches (Gregory et al., 2021).

Preface



Climate change and human-caused development continue to be leading stressors for wildlife as they search for adequate resources and navigate through landscapes. Therefore, there is a need for resilient landscapes to buffer against more intense natural disasters and anthropogenic developments. Riparian areas, the ecotone linking aquatic and terrestrial habitat types, show promise as resilient residential habitat and movement corridors for wildlife as this habitat type is accustomed to disturbances from streams, exhibit a more temperate climate, and contain a variety of resources for wildlife to use as food and shelter.

This thesis seeks to achieve two main objectives: 1) explore why riparian areas are so biodiverse and how land use change and climate change may impact their utility for wildlife, and 2) study specifically how development intensity and stream channel morphology influence how mammals use riparian areas. In the first chapter, I performed a literature review on the utility of riparian areas by wildlife in temperate regions. This review discussed how riparian areas show promise as resilient habitat and movement corridors for terrestrial wildlife, but that land use change and climate change could impact this ability. For my second chapter I conducted research using camera traps to survey mammal use of stream, riparian, and matrix habitat types throughout watersheds in Squamish and Maple Ridge, British Columbia, Canada. This report discussed how development intensity, stream channel morphology, and other landscape features influence how mammalian communities use these three habitat types.

From my first chapter, I suggest that riparian areas are resilient residential habitat and movement corridors for a variety of wildlife. Management towards resilient riparian areas should be unique for each landscape, consider the requirements of target species, and prioritize conserving interconnected networks of riparian habitat patches of a variety of widths throughout a landscape. My second chapter put into practice the theory of my literature review. My findings determined that riparian areas were supportive of a high diversity of mammals across a landscape. At the landscape scale, development intensity and elevation were two key indicators of habitat use by mammalian communities. However, species-specific responses were much more variable, and a species' habitat use was dependent on a suite of environmental characteristics. Therefore, I suggest that management towards resilient landscapes should prioritize inclusion of riparian areas, but in order to provide habitat for the maximum variety of biotic functional groups, management plans should be scaled to both the broader landscape and the local habitat patch.

Chapter 1. Are there heroes among the landscape? A review of how riparian areas serve as resilient habitat and movement corridors for wildlife despite land use change and climate change

1.1. Abstract

Riparian areas are complex ecotones, which permits a wide range of wildlife to use this habitat type for survival, reproduction, and movement. The ability for riparian areas to support wildlife is being threatened as land use modifications degrade habitat patches and fragment landscapes, and as climate change alters environmental conditions and the locations of ideal habitat for wildlife. This review summarizes literature on riparian areas in temperate regions and discusses the potential for riparian areas to provide resilient residential habitat for wildlife and facilitate movement throughout a fragmented landscape. I suggest that the landscape context should be used to develop conservation priorities for resilient riparian areas and management efforts should reflect the conditions required by target species for conservation. Ultimately, I propose that a step towards resilience involves conserving interconnected networks of riparian areas of varying widths throughout a landscape.

Keywords: riparian area; landscape connectivity; wildlife corridor; resilience; land use alterations; climate change; riparian management

1.2. Introduction

Wildlife live in and navigate landscapes that are composed of a variety of habitat patches connected by transitions from one patch to the next. The interface of two distinct habitat types, known as an ecotone, plays key roles in a variety of ecological processes, and promotes biodiversity and interactions among organisms (Risser, 1995; Kark, 2007). Riparian areas, ecotones which link aquatic and terrestrial habitat types, account for a small portion of total global land area, yet contain higher biodiversity per unit area than other habitat types (Pedraza et al., 2021; Singh et al., 2021). Given their abiotic and biotic variation, riparian areas support many types of wildlife (Kelsey & West, 1998), defined throughout this review as any native terrestrial vertebrate. I selected this definition in accordance with how the term "wildlife" is used for policy under the British Columbia Wildlife Act, ("… raptors, threatened species, endangered species, game and other species of vertebrates prescribed by regulation… but does not include controlled alien species"; Province of British Columbia, 2022), but I modified to include only terrestrial-dwelling species to target specific use of riparian areas.

At the habitat patch level, riparian areas are heterogeneous and experience great variability in space and time. Riparian vegetation is influenced by fluvial morphology and processes such as fluctuations in water level, erosion rates, and stream overflow (Brinson & Verhoeven, 1999). For instance, some woody vegetation can survive groundwater level drops, but severe drought can change the composition of the entire riparian forest (Dwire et al., 2018); oscillating water levels may produce habitat for both wet and dry-tolerant species (Bayley, 1995); and herbaceous vegetation have dense root systems which allow persistence despite long periods of flooding (Svejcar, 1997). Another key determinant of local riparian characteristics is disturbance. In temperate zones, some riparian areas, also called riparian forests, appear analogous with the matrix forest and possess little understory vegetation due to competition for light (Brinson & Verhoeven, 1999; Naiman et al., 1993). Some riparian areas have high light exposure and shrubby vegetation. Others may possess a combination of both shrubby vegetation and trees. Natural and anthropogenic modifications to riparian areas, including floods, grazing, and human development, push riparian areas to earlier successional stages with small trees, shrubs, and grasses that can quickly recolonize after a disturbance (Brinson & Verhoeven, 1999). Thus, riparian areas do not possess the same characteristics across a landscape. However, scaling up to the landscape-level, variation in riparian areas may be more expected, because of the predictable patterns in watersheds from their headwaters to river mouths (Malanson, 1993). Wildlife may rely on that dependability for survival in a landscape.

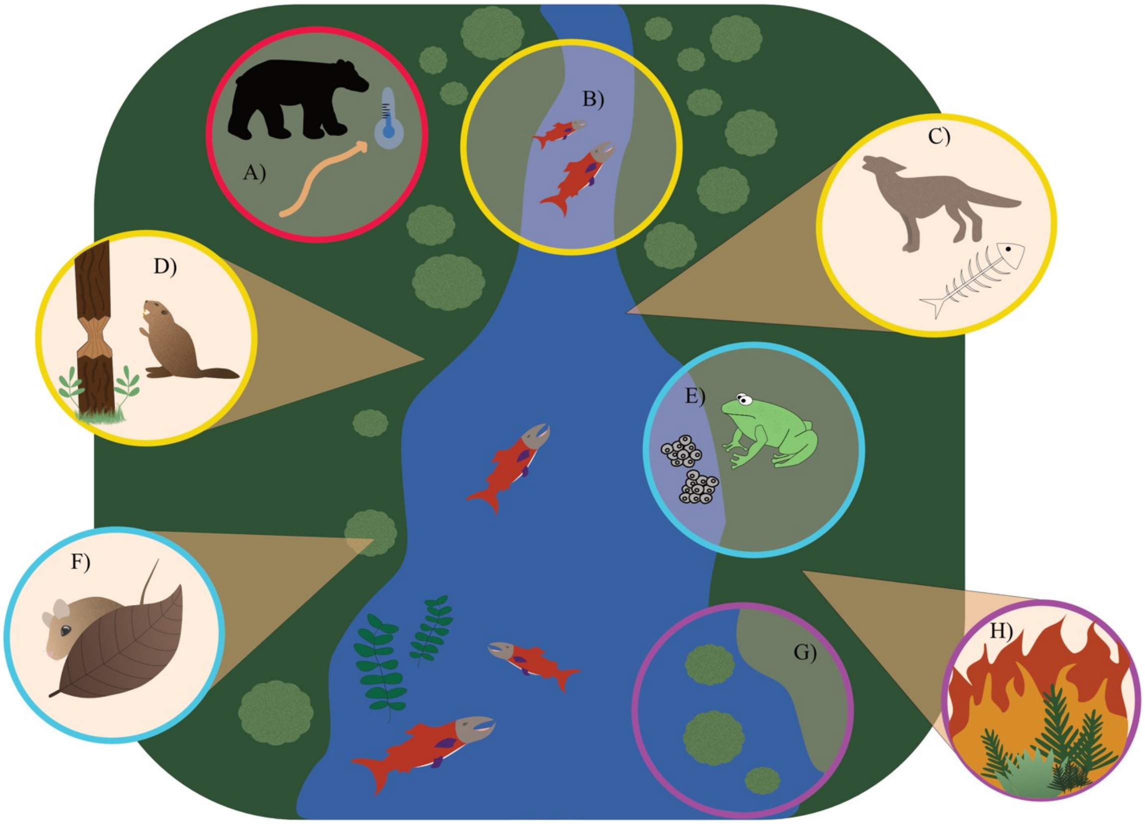


Figure 1.1. A conceptual model of how riparian areas support wildlife. The colored circles symbolize the following topics: yellow = food, blue = shelter, red = connectivity, and purple = resilience. A) Riparian areas can serve as continuous pathways throughout a landscape and facilitate wildlife movement (Krosby et al., 2018), especially at warmer temperatures because evaporated water from streams cools the air in the surrounding riparian area (Larson & Larson, 1996). B) Seasonal fish migrations have a phenological match with intense feeding periods for wildlife preparing to overwinter (Willson et al., 1998). C) Terrestrial wildlife scavenge for the dead aquatic organisms and vegetation left behind during periods of low water volumes (Sánchez-Montoya et al., 2017). D) Riparian zones feature vegetation that meets dietary needs for some species (Singh et al., 2021). E) Semi-aquatic wildlife lay eggs in streams during natural swelling events (Kupferberg et al., 2012). F) Riparian areas provide refuge from predators that may avoid this habitat type (Singh et al., 2021) and resting sites among cavities in the trees or eroded banks to escape adverse weather conditions (Weinberger et al., 2019). G) Some riparian vegetation is adapted to flood disturbance, creating a resilient habitat patch (Džubáková et al., 2015; Garssen et al., 2015). H) Riparian areas may withstand fire better than matrix vegetation due to higher soil moisture around waterways and fast growth rates (Pettit & Naiman, 2007).

In a changing world, wildlife need resilient habitat patches and landscapes in order to persist locally and globally. Ecosystem resilience can be considered as the maintenance of all major biotic functional groups despite disturbance (Holling, 1973; Holling 1996; Côté & Darling, 2010). I define resilience of biotic functional composition in this review at two spatial scales: patch-level and landscape level. Each of these scales could be resilient to different disturbance types (e.g., climate change, land use change, natural disturbance) to different extents. Resilience within habitat patches is measured by the ability for a given patch to exist in several different states without losing its functions after disturbances occur (Holling, 1973; Holling et al., 1995; Wallington et al., 2005). Resilient patches maintain resources and environmental conditions necessary for wildlife survival and reproduction despite disturbances, through mechanisms such as habitat complexity, genetic diversity, high species richness and diversity, and functional redundancy (Biggs et al., 2020). Landscapes are comprised of a mosaic of habitat patches, and landscape resilience can be achieved even if all habitat patches are not resilient so long as the patches are interconnected and allow for the exchange of resources, energy, and organisms throughout the landscape (Chambers et al., 2019). This creates a management challenge, as patches experience different natural and anthropogenic disturbances and respond differently to disturbances, and as a result, landscapes will have varying levels of resilience (Chambers et al., 2019). For example, a landscape comprised of only farmland will be impacted by a flood differently than versus a landscape of varying topography with streams and riparian areas to process increased water volumes, with the latter having higher resilience. Furthermore, different habitat patches in a landscape are linked by the movement of materials and organisms (Table 1.1), such that management of one patch may alter another, or conversely local management of a patch may fail to produce intended outcomes due to dynamics in connected patches. While patch-level conservation efforts might be successful locally, many wildlife species rely on multiple habitat patches in different times and places, and successful management requires considering the landscape holistically (Chambers et al., 2019; Weise et al., 2020).

Riparian areas, and their productivity and heterogeneity, are important components to consider when managing for resilience. For example, riparian areas contain microhabitats with unique climatic conditions and resources that support both generalist and specialist wildlife (Krosby et al., 2018; Mislan and Helmuth, 2008). For species that have small home ranges and specific resource requirements, single microhabitats are critical for survival; in contrast, generalist species with large home ranges can move to find resource requirements in multiple habitat patches (Mislan and Helmuth, 2008). Microhabitats also assist in maintaining resilience by contributing to habitat complexity, and heterogeneity increases the likelihood that a habitat patch will still support wildlife in the event of a sudden climatic shift or natural disaster (Dwire & Kauffman, 2003). If a landscape has interconnected microhabitats, ecological theory and limited empirical evidence suggests that sink populations can be bolstered from source habitat patches and redundant species can fill ecological niches (Hauser & Leberg, 2021; Loreau et al., 2003; Murphy, 2001).

This review introduces a conceptual framework in which riparian areas in temperate regions act as both resilient habitat for wildlife, providing food, water, space, and refuge from predators, and as corridors to facilitate movement across a landscape, thus serving as a keystone to landscape-scale conservation and management (Figure 1.1). In the next sections, I will discuss how characteristics of riparian areas such as riparian width, stream size, flow regime, dendritic properties, and location within a landscape affect the utility of riparian areas for wildlife as habitats, movement corridors, or both. Next, I outline how land use change and climate change alter the ability of riparian areas to provide wildlife with food, water, and space, refuge from predators, and connectivity among habitat patches, as well as affecting the resilience of riparian habitat patches and the landscapes in which they are situated. Finally, I suggest management strategies for riparian areas with landscape resilience in mind.

Table 1.1. Connections among aquatic, riparian, and matrix habitat types in watersheds.

Donor and Recipient Habitat Type	Contribution/Mechanism from Donor Habitat Type	Effects on Ecological Characteristics of Recipient Habitat Type
Riparian area to aquatic habitat type	1) Overhanging vegetation 2) Deposition of vegetation, rocks, and finer sediment 3) Woody debris inputs 4)Shared habitat for semiaquatic wildlife	1) Water temperature regulation (Naiman et al., 1993) 2) Definition of the physical habitat structure (Trevarrow & Arismendi, 2022; Wohl, 2017a) 3) Provision of physical habitat; substrate for germination of some plant and tree species (Newton et al., 1996); crossing structures for terrestrial animals (Trevarrow & Arismendi, 2022) 4)Transfer of resources, materials and energy into aquatic habitat types (Smith & Mather, 2013)
Aquatic habitat type to riparian area	1) Flow variation into floodplain 2) Water flow 3) Influence on groundwater dynamics 4) Fluxes from organismal life history events (migration, emergence)	1) Definition of riparian zone width (and thus habitat patch size) and disturbance regime (and thus habitat characteristics) (Naiman et al., 2005b) 2) Deposition of sediment and nutrients and provision of soil moisture, determining growing conditions for vegetation (Naiman et al., 2005a) 3) Regulates soil moisture, determining growing conditions and fire sensitivity (Pettit & Naiman, 2007; Reeves et al., 2006) 4) Nutrient and organic matter transfers enrich riparian areas (Willson et al., 1998)

	5) Shared habitat for semiaquatic wildlife	5) Transfer of resources and energy into terrestrial habitat type (Ben-David et al., 1998)
Riparian area to matrix habitat type	1) Shared habitat for terrestrial wildlife	1) Transfer of resources and energy into matrix habitat type (Lopez et al., 2022)
Matrix habitat type to riparian area	1) Downslope movement of water, materials, and resources 2) Shared habitat for terrestrial wildlife	1) Deposition of sediment and material, providing physical habitat structure and resources (Naiman & Décamps, 1997) 2) Transfer of resources and energy into riparian habitat type (Kauffman & Krueger, 1984; Stoffyn-Egli & Willison, 2011)

1.3. Riparian areas as wildlife habitat

Provision of resources, shelter, and space are key functions of wildlife habitat, and an area's utility for a given species will depend on these factors. The ability for riparian areas to supply food, water, refuge from predators, and sufficient space depends on the species attributes and several characteristics of the riparian area itself. Here, I outline how riparian width, stream size, and flow regime shape the quality of riparian habitat.

1.3.1. Riparian width

The physical width of a riparian area plays an important role in supporting wildlife (Graziano et al., 2022). The amount of space required for a habitat patch to have all resource and environmental condition requirements varies by species, but for riparian obligate species, a certain width of riparian area may be required before individuals will continually use the habitat (Stoffyn-Egli & Willison, 2011). The effect of riparian area width on patch utility also depends on other traits of the focal species. Narrow riparian areas or zones that have been recently disturbed by logging, development, or natural processes such as fire or flood, might be preferential for edge-seeking species so long as they do not come into conflict with humans and their developments (Marczak et al., 2010; Meiklejohn & Hughes, 1999). In contrast, interior species struggle to survive in edge habitat, so wide riparian areas are needed to create the distance from edge habitat (Larsen-Gray & Loehle, 2022) and some species may avoid riparian areas altogether (Burbrink et al., 1998; Marczak et al., 2010). To highlight a few examples, Haegen and Degraaf (1996) found increased predation pressure by red squirrels (*Tamiasciurus hudsonicus*) and blue jays (*Cyanocitta cristata*) on prey bird nests in narrow (20 – 40 meter) riparian buffer strips created by commercial clear-cutting events; most amphibians reside in the matrix habitat type until they move to the stream to reproduce, but they cannot respond well to the edge conditions in a narrow riparian area's microclimate, which are significantly different from the undisturbed matrix habitat type (Marczak et al., 2010); and Aune (1994) found that the grizzly bear (*Ursus arctos*) utilized riparian areas in the continental climate of Montana, but avoided edge conditions where there was a high likelihood of human contact.

Riparian widths differ due to the intensity and frequency of disturbances caused by a stream's hydrologic regime (Loheide & Booth, 2011). These disturbances could be due to the stream's width, depth, water velocity, turbulence, substrate material, or floodplain position (Gurnell et al., 2012; Loheide & Booth, 2011; Naiman et al., 2005b). For example, streams with steep and rocky banks might not have large floodplains, which yield narrow riparian areas as disturbances from the water will not extend far onto land, allowing later successional forests to grow near streams (Naiman et al., 1993). In contrast, rivers cutting through flat landscapes might have large floodplains, which produce wide riparian areas (Swanson et al., 1998). It is difficult to parse out the co-dependence of these stream variables, however, each unique scenario may change how wildlife use the riparian area. For instance, difficulty moving through deep or fast-flowing water or steep or unstable streambanks could limit some species' access to a local riparian area (Coombes, 2016).

Management consideration: Conserving riparian areas of a variety of sizes is best for maintaining biodiversity, as wildlife have ample habitat patches to choose from (Graziano et al., 2022). However, in developed spaces, a focus towards conserving wider riparian buffers could capture various riparian widths, including wide riparian areas, which would absorb some adverse effects of anthropogenic activities and provide resources and environmental conditions for both edge and interior species (Rodewald & Bakermans, 2006).

1.3.2. Stream size

In addition to the context of the width of a riparian area, the width of the streams and the streams themselves affect how wildlife use the adjacent riparian areas. Stream size is relatively understudied in the context of riparian function yet may play an important role in determining the utility of riparian areas for wildlife. For example, the majority of conservation efforts focus on medium and large-sized streams; however, small streams make up a significant portion of the total stream length within a riverine network (Finn et al., 2011; Richardson et al., 2005). Small streams vary a lot in their environmental conditions, which has been shown to create high beta diversity across the stream networks (Finn et al., 2011; Meyer et al., 2007); future research is needed to determine whether this would lead to high beta diversity for terrestrial species using stream and riparian habitat types as well. Larger streams and rivers often traverse less steep habitat patches, creating riparian areas which may be preferential habitat for some species compared to steeper terrain. Medium and large-sized streams can typically host a higher total aquatic biomass (Junk et al., 1989), which may serve as a steady food source for terrestrial wildlife, however, deeper waters and faster flows may introduce access barriers for wildlife.

Seasonal changes result in predictable flood regimes and flood disturbances in large streams (Junk et al., 1989), and the intensity of riparian and stream habitat type use by certain wildlife may track these seasonal changes. Small streams have frequent but less severe disturbances, so wildlife will have a variety of uses of this habitat type year-round. With any stream size, occasionally severe disturbances occur, which can make large landscape alterations that can reset the successional path of the surrounding area (Wohl, 2017b), presenting new opportunities for species to colonize. For wildlife, this could mean either an influx or elimination of new food sources and space.

1.3.3. Flow regime

Intermittent streams have a significant dry period during a year. There is limited empirical research on how this dry phase influences the presence of wildlife despite intermittent streams being as common as their perennial counterparts (Datry et al., 2014; but see Moidu et al., 2023; Sánchez-Montoya et al., 2023). Intermittent streams themselves act as ecotones and there are significant resource and energy exchanges between aquatic and terrestrial habitat types (Figure 1.2; Steward et al., 2012). During the dry period, streambeds may resemble terrestrial habitat types, in one sense extending the area of the riparian zone and providing additional terrestrial food resources; however, without water flow, other benefits of riparian areas (water availability, temperature and moisture regulation) may wane, and the riparian areas around dry streams may become less important as wildlife habitat.

> ***Management consideration:*** Changes to the hydrologic regime will influence sediment nutrient content and texture, which may exclude certain vegetation from establishing in a riparian area.

Variation created by intermittent streams throughout a year could contribute to the resilience of the riparian area. Stream drying promotes heterogeneous vegetation (Milner et al., 2023) and the subsequent recolonization of terrestrial vegetation that occurs in the stream provides new food sources for wildlife. For example, one study by Sánchez-Montoya et al. (2022) found that ungulates and herbivores extended their feeding range into streambeds during dry phases and carnivores, like the red fox (*Vulpes vulpes*), scavenged for dead aquatic organisms.

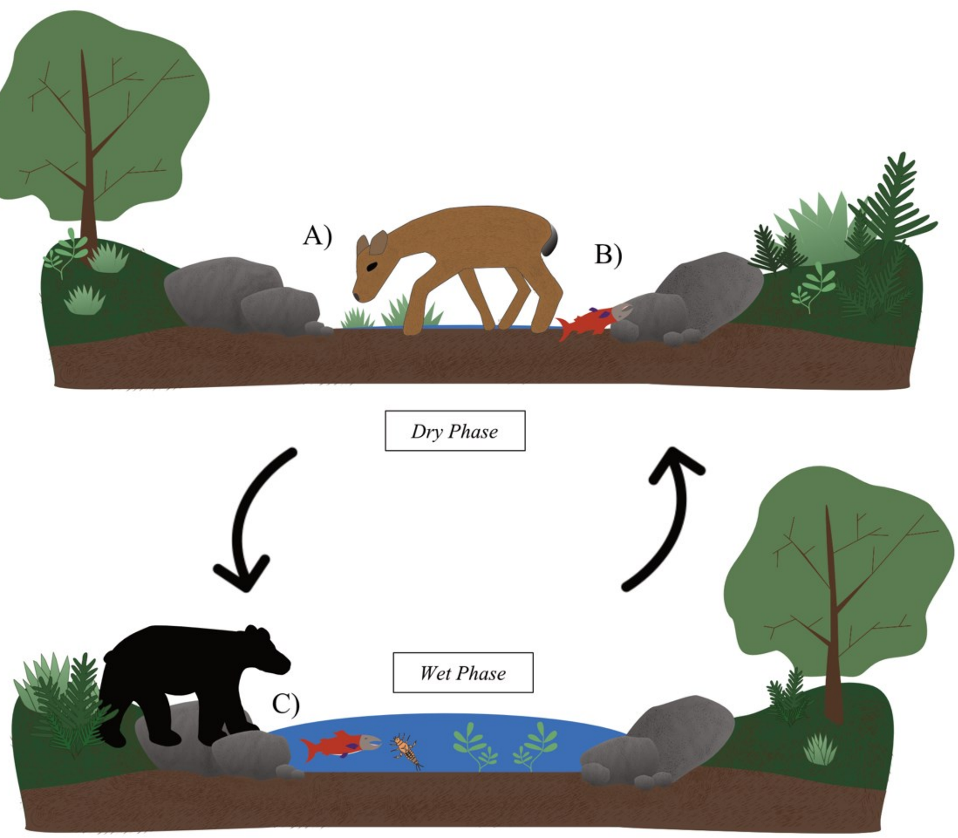


Figure 1.2. A theoretical depiction of how wildlife might use intermittent streams. A) Intermittent streams serve as movement corridors for wildlife (Sánchez-Montoya et al., 2016). B) Pioneer terrestrial plants colonize dried streams, providing food for herbivorous wildlife, while terrestrial scavengers take advantage of the aquatic species left on the streambed (Steward et al., 2012). C) Aquatic organisms are present in the wet phase (Bogan et al., 2017), which terrestrial wildlife hunt.

1.4. Riparian areas as wildlife movement corridors

Riparian areas also serve as important movement corridors for wildlife in some contexts. Studies have shown that riparian zones promote functional connectivity for wildlife, including birds (Dallimer et al., 2012), herpetofauna (Burbrink et al., 1998), and terrestrial mammals (Hilty & Merenlender, 2004). Crucially, riparian areas are distributed throughout watersheds and thus have the potential to connect a variety of habitat patches

(Fremier et al., 2015). Just as for their use of riparian areas as habitat, characteristics of riparian areas will determine the extent that different species choose to use them as movement corridors.

1.4.1. Riparian zone width

Many of the mechanisms creating narrow riparian zones may limit the suitability of a riparian area as a movement corridor. For example, if riparian areas are very steep and filled with debris, then it may be difficult for some species to navigate (Badgley, 2010), and they may find paths of less resistance in stream or matrix habitat types. Narrow riparian areas might become ecological traps for prey using these habitat patches as movement corridors as edge habitat may facilitate predation. For example, a study conducted by Hilty and Merenlender (2004) found that in northern California, mammalian predators were using riparian corridors adjacent to vineyards 11 times more than the matrix. Conversely, wide and flat floodplains may serve as excellent corridors for some species (Krosby et al., 2018). At the landscape-level, interconnected habitat patches via riparian corridors of a variety of widths will allow wildlife to select habitats that encompass the resources and environmental conditions they require. Therefore, this landscape would be highly resilient because the habitat patches are complex, host a high species richness and diversity, and are interconnected throughout the landscape. Landscapes that only contain narrow riparian corridors will exclude certain species not equipped to survive in these habitat patches. Consequently, these landscapes will be less resilient by having a lower species richness, potentially losing functional redundancy, and having less habitat complexity.

1.4.2. Stream size

Small streams rely heavily on riparian inputs, and as such can also collect blockages of woody debris, which serves not only as valuable habitat features for aquatic species, small mammals, and birds, but provides stream crossings for terrestrial wildlife (Steel et al., 1999). Small streams, being narrower and generally shallower, may be particularly important for small animals who would have difficulty crossing large streams

(Bohdal et al., 2016). The size of the stream also regulates temperatures of the riparian area, where larger volumes and surface area of water can better buffer against temperature peaks (Larson & Larson, 1996), which may facilitate wildlife movement particularly during the hottest times of the year.

1.4.3. Flow regime

During the dry period, the bare streambed can facilitate movement more easily than riparian areas or matrix habitat types, and Sánchez-Montoya et al. (2016) determined that dry riverbeds were used by a range of wildlife, particularly in reaches that were densely vegetated. Presently, protections of intermittent streams are lacking at both national and international levels, but their potential to act as movement corridors for wildlife may be particularly important as human-altered landscapes limit available habitat for wildlife (Steward et al., 2012).

1.4.4. Dendritic connectivity

Viewed from space, riparian areas form dendritic networks by lining the sides of stream reaches throughout a watershed. As part of this dendritic network, riparian areas stretch continuously throughout the landscape, forking from the main pathway like tree branches (Campbell Grant et al., 2007). The dendritic properties of a riparian area provide a pathway for wildlife to navigate through as they forage, seek new habitat patches for migratory purposes, or in response to habitat loss or climate change. While distance along the dendritic network may not necessarily be the shortest path from A to B, if riparian areas provide suitable habitat for wildlife and protect them from predators and humans, then the dendritic network could form a movement network of continuous safe space to navigate. There is mounting evidence suggesting that riparian areas are important for regional connectivity and population dispersal in a variety of biomes (Aronson et al., 2017; Atkinson & Lake, 2020; Hauser & Leberg, 2021; Santos et al., 2016). For example, cougars (*Puma concolor*) have been observed using riparian areas in the Midwest United States to avoid farmland on their way to larger reserves (LaRue & Nielsen, 2008). However, there are several sources that may break the continuity of riparian areas. Natural disruptions include the formation of lakes, knickpoints, and biological barriers such as beaver dams (Lokteff et al., 2013; May et al., 2017). Humans also disrupt the river continuum by constructing dams and reservoirs and by burying waterways in developed areas (Maloney & Weller, 2011).

1.4.5. Position within a landscape

Wildlife must stay in habitat patches that contain necessary resources for survival or facilitate important life history events and will typically move along pathways that provide the least amount of resistance navigating the terrain (Cline & Hunter, 2016; Williams et al., 2012). Riparian areas that are far from human development are typically best suited as wildlife corridors (Krosby et al., 2018). An important exception are species that thrive in developed spaces and will prefer to move through developed matrix habitat patches (Brady et al., 2011). Topographically complex regions host a high species richness because there is tremendous biotic and abiotic diversity within these mountainous landscapes, and they are typically far from human development (Badgley, 2010). However, some mountainous headwaters may be too steep and treacherous for certain species to move through or lack proper food sources compared to flatter and lower elevation habitat patches downstream (Badgley, 2010). Yet, high quality riparian corridors in lowland habitat patches are among the least protected from human development (Hauer et al., 2016; Krosby et al., 2018).

Management consideration: There is an urgent need to conserve downstream riparian corridors to facilitate movement for species that cannot navigate mountainous landscapes.

Proximity to other landscape features may also be required by certain species. For example, many herpetofauna rely on the connection from matrix to streams for residence in the former and reproduction in the latter (Burbrink et al., 1998). Semi-aquatic species, like freshwater turtles, require connectivity of riparian areas to wetlands for successful nesting on land (Semlitsch & Jensen, 2001). Riparian corridors also have the potential to link larger protected reserves (Fremier et al., 2015), which may be necessary for interior-seeking or elusive wildlife.

1.5. What are the repercussions of land use change?

Human-caused development has decimated habitats, permanently fragmenting once continuous landscapes or eliminating entire swaths of useable habitat patches for wildlife (Haddad et al., 2015). Both habitat loss and fragmentation affect wildlife use of riparian areas by altering habitat quality (food and water availability, refuge from predators, and space), movement connectivity, and landscape resilience. Habitat loss most strongly impacts the amount of available habitat for wildlife, which could negatively affect the quality of remaining habitat patches. Fragmentation reduces habitat patch size, alters interior conditions of the patches, and limits connectivity between patches. Presently, human development is pushing wildlife into three categories of space use: those able to persist in developed spaces, those able to adapt or live on the outskirts of urban environments or in other developed spaces (e.g., farmland, resource extraction sites), and those that avoid developed areas entirely and retreat to the remaining undeveloped habitat patches (Alberti, 2005). Wildlife will fall into one of these three categories based on their level of tolerance of the matrix habitat type (Brady et al., 2011), though may be able to persist in areas that lack some resource or condition requirements as habitat may be suitable for wildlife who occupy an area which contains enough of their requirements, if not all of them (Hall et al., 1997). In the context of alteration to riparian areas and their surrounding matrix, riparian areas have the potential to act as either habitat for matrix tolerant or matrix adaptable species, especially if the riparian area is narrow and in close proximity to developed habitat patches, or as movement corridors for matrix avoidant species.

Loss of riparian areas most often limits the availability of food by decreasing foraging opportunities, thus heightening competition (McIntyre, 2014). However, in some cases, such as the conversion of natural habitat to agricultural fields, food availability can increase for certain species (Baldwin et al., 2013; Becker et al., 2015).

Fragmentation of riparian areas creates a large edge effect around a disturbance (Murcia, 1995). In a wide and uninterrupted riparian area, there is a large buffer between the edge and the interior habitat (Collinge, 1996). As the riparian area becomes fragmented, edge habitat increases, and with it wind patterns, light, temperature, and moisture levels change, all of which affects which food sources can exist in this habitat patch (Bender et al., 1998; Collinge, 1996). Introduced edge habitat and accompanying warmer temperatures also reduces both water availability and quality (Mullu, 2016). Vegetation loss around streams destabilizes streambanks, which can have cascading effects on the temperature, light availability, flow regime, and aquatic prey of adjacent reaches (Hickin, 1984; Mullu, 2016). For certain generalist or edge-seeking species, habitat fragmentation is of mild concern, as these species can adapt their diet or learn quickly from their new environment (Hunt & Hodgson, 2010). So long as these species do not have to compete for remaining resources, they may persist in exposed habitat patches (Bender et al., 1998; Fahrig, 2017). Interior species, on the other hand, experience adverse effects from habitat fragmentation (Bender et al., 1998), as they are ill-suited to exposure to windy and warmer conditions or being in closer proximity to humans. In addition to the simple reduction in the size of riparian areas, which diminishes the available space for wildlife use, land use change degrades the quality of the surrounding matrix, which can have equally profound effects on populations (Prugh et al., 2008).

Degradation of aquatic habitat patches can also affect the habitat quality of riparian areas. Should fragmentation sever the continuity of a stream, edge habitat is introduced to the aquatic ecosystem around the fragmented area (Fuller et al., 2015). Riverine fragmentation and its consequences to obligate aquatic organisms will impact what food is available for wildlife in riparian areas (Fuller et al., 2015), the extent to which resources are transferred from water to land (Sabo & Hagen, 2012), and thus which terrestrial species are present. Terrestrial land use change, such as agricultural development, degrades the ecological integrity of waterways, heightening the likelihood for erosion, faster water velocity, and channel migration (Hickin, 1984). In return, the instability of the stream puts the riparian area and its resources at greater risk for destruction from flooding. This will ultimately decrease the resilience of the riparian area. Likewise, dams and hydropower stations installed for energy production can alter the hydrologic regime of a stream, result in unexpected flooding of the riparian area (Brosse et al., 2022, Naiman et al., 1993). Dams have lasting ecological implications, as the reduced water flow downstream heightens the likelihood of streambed drying, catalyzing instability throughout the food web (Steward et al., 2012), including in riparian areas.

Fragmentation to riparian areas resulting in the increase of exposed habitat patches can facilitate predation (Lidicker, 1999). Certain predators are naturally more concentrated around open areas as it is easier to spot prey (Gates & Gysel, 1978). As well, instances of linear disturbances, like trails or resource extraction sites can provide easier movement pathways into riparian areas for some predators (Miller & Hobbs, 2000). Threats to shelter and refugia from predation would decrease the quality of habitat from a prey perspective but would benefit predators. On the other hand, predators intolerant of human activity and variable climatic conditions face greater competition with limited hunting space and challenges capturing prey tolerant of exposed habitat patches (Brodie et al., 2015; Leal et al., 2012). This would result in population declines for predators, but potentially benefit their prey, if the prey are more tolerant of human activity (Berger, 2007). Thus, for some species interactions, human development in riparian areas could potentially lower predation pressure.

Land use change via habitat fragmentation affects connectivity, and the ability of riparian areas to serve as wildlife movement corridors, in multiple ways. Landscapes are dynamic and habitat features are constantly being replaced and renewed by temporal changes and biotic interactions (Dietrich & Perron, 2006). Naturally occurring riverine processes, such as stream migration and diversion, will conflict with more static patterns of human development (Parrott & Meyer, 2012). This could result in safety risks for humans, particularly concerning flood damage, however, there are also major ecological implications, including dry or degraded streams and discontinuous riparian areas (MacKenzie et al., 2022). Developments may both facilitate and hinder wildlife movement through a landscape; on the one hand, dried streams might be easier pathways that are unblocked by vegetation, while on the other hand, warmer temperatures, less availability of food, water, and space, and industrial impediments may introduce barriers for wildlife. As well, humans disproportionally develop in lowland areas (Zwick, 1992), which may cover potential refugia for wildlife unable to access higher elevations, push wildlife into less productive habitat patches, and block movement corridors to suitable patches. In the context of resilience, wildlife unable to move due to anthropogenic barriers could risk extirpation without adequate resources, thus lowering the biodiversity of the landscape and the functional redundancy needed to withstand future disturbances.

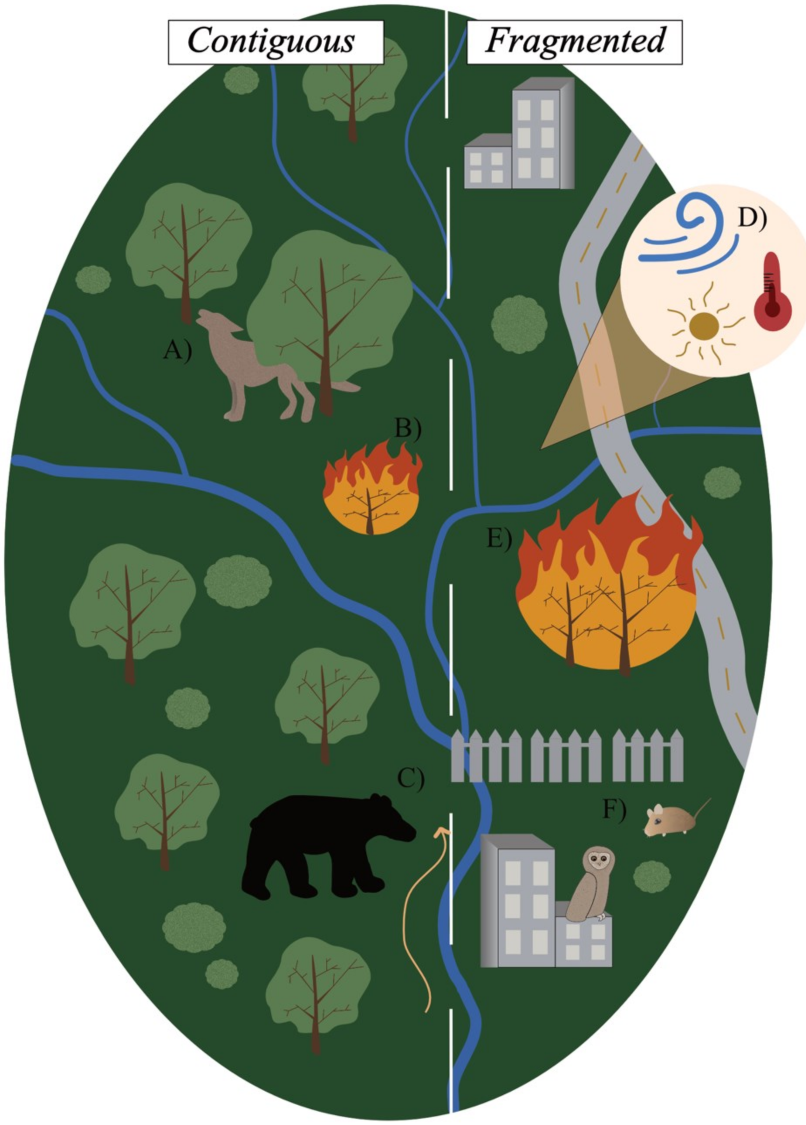


Figure 1.3. **Positive and negative outcomes of riparian zones without (left) and with (right) habitat fragmentation.**
Examples in contiguous habitat patches includes A) environmental conditions and resources for interior species, B) fires are less impactful in resilient habitat patches, and C) potential movement corridors through connected landscape. Examples in fragmented habitat patches include D) introduced edge habitat exposes wildlife to new environmental conditions, E) fires are more severe for remaining undeveloped patches, and F) some species are more common in fragmented landscapes.

Land use change is also complicating strategies for landscape resilience through the rapid homogenization of riparian zones (Alberti, 2005). Human modifications of land have simplified habitat patches over time, meaning that the vegetation composition is limited to a few generalist species (Naiman et al., 1993). Natural disturbances are stifled for human safety concerns, and instead replaced with habitat loss and fragmentation (Alberti, 2005). Variation in ecological communities in developed landscapes typically results from the introduction of exotic and invasive species (Brice et al., 2017). Microhabitats contributing to habitat complexity are also being eliminated and as a result, specialist species struggle to find ideal habitat (Devictor et al., 2007). Isolated habitat patches reduce overall genetic diversity over time (Fahrig, 2003), which can lead to effects ranging from decreased fitness of individuals to a reduced potential for the species to respond to landscape changes. Ultimately, without structural and functional variety, species risk homogenization as only those well-adapted to developed environments will survive (McKinney, 2006).

1.6. How is climate change altering riparian areas?

Unpredictable and extreme climatic shifts are occurring faster than the rate at which wildlife can adapt to them. Climate change affects wildlife use of riparian areas by altering annual temperatures, the amount and timing of precipitation events, and changes to the amount and timing of water delivery by streams to riparian areas. It is important to recognize as well that climatic changes to riparian areas extend well beyond the bounds of this discrete habitat type due to the co-dependent relationships ecotones have with their surrounding habitat types (Braudrick et al., 2009). Climate change also presents itself differently given that environmental conditions are not uniform within a landscape and unique biota and ecological processes occur in specific locations.

Warming temperatures throughout a watershed may result in new climatic zones in certain regions, which may take on new riparian vegetation (Doretto et al., 2020; Dwire et al., 2018; White et al., 2021). Changes in environmental conditions and vegetation distributions will alter the location of suitable riparian areas for any given species. Some wildlife who are unable to move to track shifts in abiotic conditions

(Louthan et al., 2015; Van der Putten, 2012) or biotic interactions (HilleRisLambers et al., 2013), or cannot cope with new environments (Hetem et al., 2014) may be unable to access suitable food sources. However, some wildlife benefit from climate change (O'Brien & Leichenko, 2003), and the introduction of new vegetation to an area or the redistribution of vegetation may be favorable, particularly for species whose primary food source is enhanced or those able to adapt their diets. Temperature increases may also deem riparian areas more important for wildlife if the matrix is hotter and less hospitable (Seavy et al., 2009), as their proximity to water and shading vegetation provides thermal refugia for wildlife (Gashaw et al., 2015.; Larson & Larson, 1996). Because riparian areas are naturally resilient, should extremely high temperatures or low levels of precipitation persist in a landscape, wildlife can seek milder environments in riparian areas. In this sense, riparian areas have the potential to serve as long-term climate refugia (Wilkin et al., 2016; Zhang et al., 2023).

Climate change generally redistributes precipitation and increases extreme droughts and floods (O'Gorman, 2015; Trenberth, 2011). Influences to riparian areas consequently come from hydrological changes (Poff et al., 1996), the extremity of which depends whether the stream is snowmelt or rain-fed (Raymondi et al., 2013). Snowmelt streams release water throughout the warm season from snow reserves in the winter. With climate change, precipitation in the winter may be rain instead of snow, which inhibits the mountains from accumulating enough snow to provide water throughout the entirety of the warm season (Poff et al., 1996). Rain-fed streams or mixed rain and snowmelt streams may experience more extreme flooding during peak flows throughout the year (Raymondi et al., 2013). For wildlife, this could be detrimental for those reliant on vegetation and aquatic species lost during droughts or floods. Riparian connectivity may also be impacted by floods if habitat features are modified in the aftermath of the flood, reducing suitability for wildlife (Perotto-Baldivieso et al., 2011). However, flooding may increase the connectivity potential for wildlife should it result in increased floodplains, which will expand the width of riparian areas and facilitate conditions for species preferential to large riparian areas.

Climate change will also alter the amount and timing of water delivery to streams, and subsequent impacts on riparian areas. For example, warming is causing snowmelt to begin earlier in the spring season (Adam et al., 2009). In some cases, climate change may elongate the duration of the flood, expand the floodplain, or begin flooding earlier in the year (Trenberth, 2008). This can be detrimental to wildlife who rely on oscillating water volumes to perform life history events (Donnelly & Crump, 1998). An earlier snowmelt also leaves stream reservoirs with low volumes of water throughout the summer, making it more difficult to feed streams during the driest months of the year (Qi et al., 2022). Only drought-tolerant species can survive in this new climate (Dwire et al., 2018). Wildlife who primarily browse on drought-tolerant plants may have a competitive advantage in this situation. If there is less streamside vegetation, sediment will erode back into streams, forming a feedback loop that decreases the size of the riparian area (Vandenberghe, 1995). Streams without riparian vegetation also risk drastic temperature peaks and simplified aquatic habitat, making it more difficult for fish and macroinvertebrate species to find food and seek shelter (Arnaiz et al., 2011; Broadmeadow et al., 2011). In certain cases, once perennial streams may become intermittent (Datry et al., 2014), which may restrict available aquatic food sources for wildlife.

1.7. Management of riparian areas

1.7.1. Riparian areas in the context of landscape resilience

Climate change is forcing wildlife populations to extend their distributional ranges (Coristine & Kerr, 2011). Coupled with the reality that humans have extensively developed worldwide, wildlife face challenges navigating to ideal habitat patches, and depending on the degree of habitat loss and fragmentation, range shifts may be impossible for certain species (McInerny et al., 2007). Human alteration of natural disturbances, like higher-intensity wildfires, accompany climate change and prove problematic for wildlife in remaining intact habitat patches. One promising solution to combat these compounding threats to landscape resilience is to focus conservation efforts on riparian areas, which have a high likelihood to rebound despite climate change and land use alterations due to their complexity and diversity (Seavy et al., 2009).

Resilient riparian areas will have mechanisms to process major disturbances, such as floods, regardless of the size of the adjacent stream. For instance, riparian areas near wide streams might have a large surface area to absorb the bigger floods, so long as healthy vegetation is present to stabilize the streambanks and maintain healthy soils (Gashaw et al., 2015). In these cases, it is important to manage in a way that does not alter this buffering capacity. Riparian areas near smaller streams that are equipped with flood-tolerant vegetation (Džubáková et al., 2015; Garssen et al., 2015) or highly regenerative vegetation can rapidly reproduce shelter and food for wildlife after a flood event. While local habitat patches may be more sensitive to disturbances, entire watersheds may be more resilient if riverine networks are linked from the headwaters to the mainstem (McCluney et al., 2014). There is functional redundancy in habitat patches at the landscape-level, such that should one habitat patch be less productive after a disturbance, wildlife can move to similar habitat patches while the disturbed patch is in recovery (McCluney et al., 2014).

In order to optimally support wildlife, riparian areas should be protected to maintain continuity throughout a landscape. Landscape connectivity can alleviate stress from habitat fragmentation and climate change and promote landscape resilience. Connectivity to surrounding habitat types allows for exchanges in resource subsidies between riparian areas and neighboring habitat types, increasing landscape resilience. Should the landscape experience a disturbance, wildlife corridors can facilitate movement to new habitat patches that can withstand the disturbance (Forman, 1995). These habitat patches are linked either by continuous natural pathways or stepping-stone connections (Forman, 1995). The key is that the habitat patches contain enough variation between them, either spatially or ecologically, that one disturbance does not destroy all habitat patches within the landscape. Wildlife corridors can be defined at various spatial scales, ranging from local linkages between neighboring habitat patches to trans-regional (Anderson & Jenkins, 2006; Liu et al., 2018). The resulting network maintains processes of unfragmented landscapes despite human development (Fischer et al., 2006). By maintaining continuity of riparian areas throughout a landscape, wildlife are presented with two options, the first being a refuge within the riparian area to escape a surrounding matrix that may be destroyed, and the second being a contiguous natural pathway to move along to reach new and undisturbed habitat patches. The latter option may be critical for species that cannot pass through or over the developed matrix habitat type.

1.7.2. Management of riparian areas as habitat

There is no "one-size-fits-all" technique to the conservation of riparian corridors. Even a decision as seemingly simple as how wide of a riparian width to conserve is not straightforward. Across the United States and Canada, riparian areas are protected up to approximately 30 meters, although this is not a consistent measurement (Lee et al., 2004). Existing legislations, such as the Riparian Areas Protection Act of British Columbia, are helpful by establishing a 30-meter buffer from development on either side of a stream (Province of British Columbia, 2023), but do not adequately account for additional pressures more developed areas may place on riparian areas. Instead, this policy is applied in all development contexts. For comparison, the Western Washington Riparian Management Zones incorporates a more flexible scale of riparian buffer widths (Washington State Legislature, 2009); however, there is no consideration of habitat use by wildlife in the language of this policy with regard to buffer width. To highlight some taxa-specific buffer width requirements, freshwater nesting turtles have been documented to need up to 150 meters from the water's edge to lay eggs (Bodie, 2001); certain birds will need riparian buffers even as wide as 175 meters (Spackman & Hughes, 1995); and amphibians need up to 290 meters for feeding and overwintering (Semlitsch & Bodie, 2003). Therefore, it is important for landscape managers to conserve riparian areas based on the conditions of each landscape, the space requirements by wildlife themselves, and the objectives of the wildlife management strategy, whether that be focused on resource availability or connectivity. For example, the degree of land use change, recreation pressure, habitat complexity and productivity, and the geological features of the landscape will determine how many individuals need to use riparian areas to survive and what width size will hold that capacity (Table 1.2; Ekness & Randhir, 2007).

1.7.3. Management of riparian zones for connectivity

Behavioral and landscape ecologists have been collaborating to better understand how wildlife move through space in order to determine how necessary riparian areas are, especially in developed environments (Ellington & Gehrt, 2019; Jokimäki et al., 2011; Lima & Zollner, 1996). For example, some species are continuously moving to follow food and water requirements (Abrahms et al., 2023), others remain residential and quickly adapt to changes in resources, and some are unable to comprehend any changes to their natural environment (Lima & Zollner, 1996). Even within a species, individuals of different sexes or those with offspring may choose habitats differently; perhaps one sex lives in or moves through habitat patches with heightened risks unlike the other sex (Boulanger & Stenhouse, 2014). Managers can quantify the probability of movement by measuring landscape permeability (Keeley et al., 2021), which can be defined as the quality of passage through a habitat network. Understanding what choices wildlife make to move from one habitat patch to another is important in identifying which habitat types, matrix, riparian, or stream, are of highest priority for conservation (Table 1.2; Krosby et al., 2018).

Managers can get a better idea of the quality of riparian corridors by quantifying the habitat patch using indexing tools that account for a riparian area's connective abilities within a landscape, climatic conditions, biotic composition, and developmental pressure (Krosby et al., 2018). Modelling used to rank habitat patches based on riparian quality and seeking linkages to restore large area connectivity has proven useful as an optimization tool that satisfies the economic needs of humans while preserving conditions that maintain riparian function (Bentrup & Kellerman, 2004; Iverson et al., 2001; Witing et al., 2022).

As a broader strategy, riparian areas could be a valuable habitat type to include in conservation plans, such as the "30 by 30" target set by the United Nations, which strives to conserve 30% of the planet by 2030 (*UNEP in 2022*, 2023). Given the high density of streams worldwide (Downing et al., 2012), conserving even a moderate size buffer of 50 meters on either side of the stream would amount to a large area of conservation. As well, because of their dendritic properties, conservation of riparian areas maintains connectivity to different parts of the landscape. However, it is important to note that this would not address factors such as optimal riparian width and the quality of the surrounding matrix habitat type, which will additionally influence the usefulness of riparian areas for wildlife.

Table 1.2. Current gaps in our understanding and accompanying rationale on the utility of riparian corridors.

Question	Rationale
Which predators can adapt to using riparian areas when their prey increase use of that habitat type?	Interior species and apex predators have used ecotones to seek larger natural reserves and for new hunting opportunities. Evidence to date is primarily from non-temperate regions (Brodie et al., 2015; Palomares et al., 2000).
Which interior species make use of riparian areas?	Movement within urbanized spaces by elusive species may be slower and more deliberate, moving short distances to maintain cover in riparian vegetation, or exhibiting most activity during times when humans are least present (Carter et al., 2019; González et al., 2017). As well, more research is needed to address whether wide riparian areas could create distance from edge habitat or since riparian areas are naturally located at edges, being adjacent to streams, this buffer is only important in developed scenarios.
How does riparian habitat and movement corridor use depend on the landscape configuration?	The biodiversity patterns in aquatic systems are largely dependent on the dendritic network of riverine systems (Altermatt, 2013), but it remains unknown how the dendritic riparian network affects terrestrial biodiversity.
How critical is food supply for wildlife deciding to use riparian zones as movement corridors?	The absence of food sources in certain locations along a riverine network could deter a species from using that area.
How important is it to maintain riparian habitat patch continuity, and which species can tolerate discontinuities?	It is difficult to quantify the usefulness of dendritic properties of riparian areas because most terrestrial wildlife can and will move in both riparian and matrix habitat types. However, species differ in their willingness to traverse different degrees of development in the matrix.

1.7.4. Managing for habitat and connectivity simultaneously

Because aquatic and riparian habitat types are interconnected and their function is at least partially contingent upon the upstream hydrology and geomorphology, it is not enough to conserve incomplete segments of a landscape (Naiman et al., 2005c). There needs to be some degree of connectivity between different habitat patches and among stretches of riparian areas throughout a landscape. A study in northern New Zealand by Scarsbrook and Halliday (1999) concluded that if continuous conservation of riparian areas is not feasible, the discontinuous conservation will aid in maintaining ecological integrity, but warns that there may still be problems that occur in surrounding habitat types, particularly concerning stream sediment and water quality. Applying the same principles of riparian connectivity to temperate regions, landscape managers should consider the implications of severing contact between higher and lower-order streams. On land, improving riparian size and continuity could drastically increase a riparian area's ability to support wildlife and facilitate movement throughout the greater landscape. Restoration efforts targeted towards riparian areas and riverine networks, particularly of water and soil, would also improve the overall quality of resources available for wildlife to use (de la Feunte et al., 2018). Protection of riparian areas promotes the continued improvement in water and soil quality, reduces the risk of flooding, and begins to satisfy some of the habitat requirements for species at risk (Fremier et al., 2015). Therefore, conserving riparian areas may be enticing for land managers as this strategy could tack onto existing environmental legislation (Fremier et al., 2015).

Protections of riparian areas should be further dependent on the conditions needed to sustain the target species. Given that there is widespread habitat fragmentation, and thus lots of edge habitat, protecting wide riparian areas should be a priority to ensure that species with interior habitat requirements can be sustained. However, it is also important to maintain variation in the widths. For instance, edge-seeking species thrive in open and exposed habitat patches resulting from narrow and heavily disturbed riparian areas. We would lose these species from a landscape if we only protected large riparian areas. The variation in riparian widths creates a variety of conditions for the surrounding habitat patches, maintaining a heterogeneous and resilient landscape. This is especially critical in urbanized environments where human modification of landscapes is simplifying natural habitat patches. In these cases, intentional human-controlled disturbances, such as prescribed fire, may be a necessary technique to increase overall species richness and landscape heterogeneity.

Biodiversity patterns in aquatic systems are largely determined by the configuration of the dendritic riverine networks (Campbell Grant et al., 2007). It is unclear how those patterns translate to riparian areas since wildlife traverse both within and out of the network. It is important to recognize varying degrees of reliance of wildlife on riparian networks. For instance, perhaps wildlife with large home ranges may access heterogeneous headwater riparian areas to support population growth. For species with smaller home ranges, riparian areas may support metapopulations with high levels of genetic diversity.

1.8. Conclusion

Riparian areas drive a dynamic system of resource and biota exchange at the interface of aquatic and terrestrial habitat types. Given the breadth of variation in riparian morphology and vegetation composition, many types of wildlife can utilize these areas for food, water, and refuge. The ability of riparian areas to link larger natural spaces by their dendritic properties provides a promising solution to allow species persistence despite climate and land use changes. As riparian areas come in many different shapes and sizes, managers must decide which types of riparian areas to protect that will optimize wildlife use of that habitat. Managing towards landscape resilience can be achieved by maintaining connection of riparian areas of varying widths throughout a landscape.

1.9. Acknowledgements

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Chapter 2. Take a walk by the river: Exploring how human-caused development and stream channel morphology influence the utility of riparian areas for mammalian communities

2.1. Introduction

Human-caused development and climate change are causing large-scale disturbances that are reshaping local composition of ecological communities across a landscape. Human developments resulting in either habitat loss or fragmentation have reduced available food, water, and space for wildlife, thus changing local environmental conditions that make up species' niches (McIntyre, 2014; Murcia, 1995). For some species, habitat fragmentation also prevents continuous movement pathways for wildlife through a landscape, while for others, habitat modifications may facilitate movement (Dickie et al., 2017). Consequently, wildlife are forced to live in close proximity to development and face higher levels of competition within the patches of undeveloped habitat should population densities remain the same (Alberti, 2005). As an additional stressor for wildlife, climate change is altering local resource composition at unprecedented rates. Warmer temperatures are shifting regional climatic zones, and subsequent changes to predominant vegetation follow (Gayton, 2008). Climate change is also increasing fire and flood severity (Flannigan et al., 2000; Trenberth, 2011). This alters the timing and amount of space (Abrahms et al., 2023) and water (Adam et al., 2009; Poff et al., 1996) available for wildlife and puts pressure on species to seek refuge from these events. At a local scale, community composition shifts as some species unable to find adequate resources successfully move to more suitable habitat patches and those unable to move risk extirpation, while for other species, these changes may be advantageous to their survival (Hunt & Hodgson, 2010).

Landscapes comprise watersheds which stretch from higher elevations to valley bottoms and include a variety of aquatic and terrestrial habitat types such as waterways, riparian areas, and terrestrial matrix habitat. Development and climate change are unfolding on landscapes where environmental and topographic features also determine where wildlife find adequate resources. One key landscape feature is elevation. Elevation is associated with a number of landscape features, such as steepness, distance from development, temperature, and vegetation composition, (Krosby et al., 2018; Moradi et al., 2020), which contribute to the habitat selection process by wildlife. Vegetation quantity is another key landscape feature which influence mammal use of a particular habitat patch, where wildlife will select habitat that meets their resource requirements for food and shelter (Abrahms et al., 2023). Salmon presence is a third key landscape feature and is especially critical in the Pacific Northwest region where this study takes place. The annual salmon migrations attract terrestrial wildlife for hunting opportunities (Gende et al., 2002). All these variables are tied to seasonality. Seasonal variation may shift when wildlife use a particular habitat type by either amplifying or dampening particular resources and environmental conditions within a habitat type. For example, the fall salmon migrations attract terrestrial wildlife to riparian areas and streams for food (Gende et al., 2002). In the summer, the milder climate of riparian areas will facilitate movement (Krosby et al., 2018), and their lush vegetation is an important food source for herbivores (Singh et al., 2021).

In this context, riparian areas show promise as useful movement corridors for wildlife and serve as refugia from climatic and development impacts because they are often at least partially protected from development, and are important habitat used by a variety of wildlife. Riparian areas are useful habitat because they are both structurally and functionally complex, which allows them to support high levels of biodiversity despite accounting for a small portion of total global land area (Pedraza et al., 2021; Singh et al., 2021). Part of the reason this habitat type is so biodiverse is because riparian areas experience high levels of disturbance from the adjacent streams (Gurnell et al., 2012; Loheide & Booth, 2011; Naiman et al., 2005). Riparian vegetation is typically adapted to these disturbances (Džubáková et al., 2015; Garssen et al., 2015), and as such is both fast-growing and heterogeneous. Situated between aquatic and terrestrial habitat types, riparian areas also feature characteristics of both habitat types, such as assimilating both aquatic and terrestrial nutrients in soils (Naiman & Décamps, 1997; Willson et al., 1998), which make them useful for many types of wildlife. Riparian areas also maintain dendritic network properties like streams (Campbell Grant et al., 2007), providing a continuous pathway throughout a watershed. Movement within riparian areas may be easier as their proximity to water and shading vegetation provide a milder climate for wildlife (Gashaw et al., 2015.; Larson & Larson, 1996). Because of these unique habitat properties, wildlife utilize riparian areas for food and water provisions (Singh et al., 2021), shelter (Weinberger et al., 2019), reproduction (Kupferberg et al., 2012), and movement and connectivity (Krosby et al., 2018).

While it is clear that riparian areas are important for some wildlife, a key knowledge gap is whether riparian areas can continue to serve as resilient habitat (i.e., maintain resources and environmental conditions necessary for survival and reproduction for diverse functional groups despite disturbances), movement corridors, and refugia in the face of climate change and human-caused development. In developed spaces, riparian areas may see increased use as habitat relative to less developed spaces because existing water quality legislation protects them, leaving riparian areas as some of the only remaining locally undeveloped terrestrial habitat (Lee et al., 2004). Conversely, development may cause riparian areas to lose their functional role as habitat should the resulting habitat fragmentation introduce extreme edge conditions (Murcia, 1995) or disrupt connectivity to other habitat types (Fremier et al., 2015). This would be critically important for wildlife with large movement ranges (Burbrink et al., 1998; Semlitsch & Jensen, 2001). Different species might use riparian areas in developed and undeveloped areas because of divergent habitat requirements, so perhaps the species richness is the same, but the composition is not (Figure 2.1). As well, some species have specific niches that require them to use one habitat type more than another. Riparian areas, while they have overlapping features of aquatic and terrestrial habitat types, may lack specific environmental conditions required by species with aquatic or terrestrial-based niches. At the same time, riparian areas provide their own niches and enhance resources and environmental conditions which support riparian obligate species (Kelsey & West, 2001).

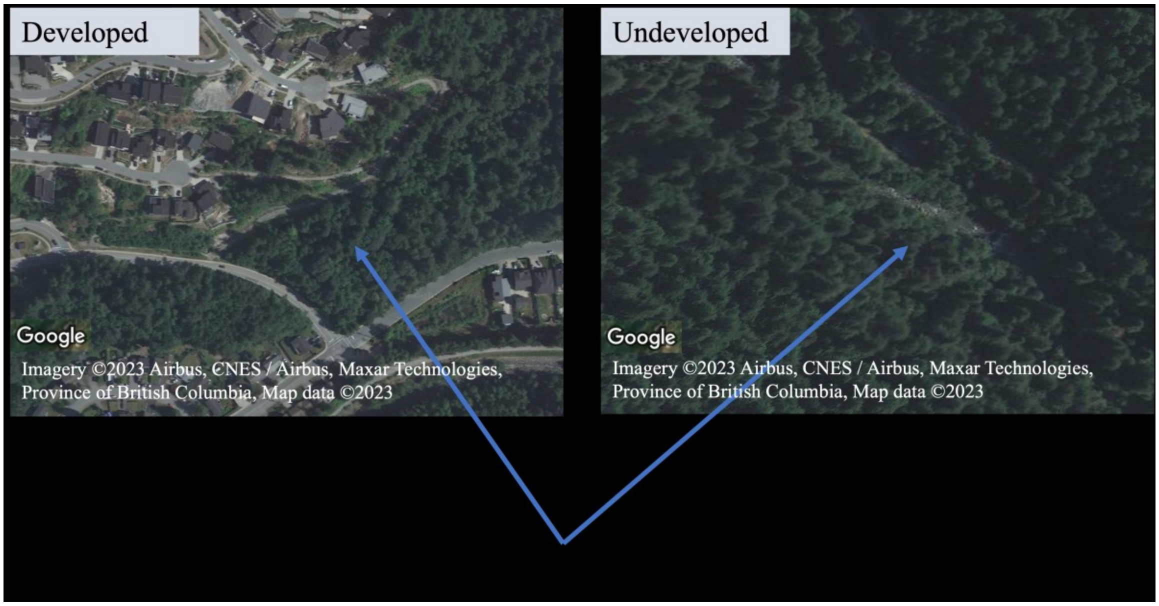

Figure 2.1. A comparison of riparian areas in developed spaces (left) and undeveloped spaces (right) in Squamish, British Columbia, Canada. Imagery ©2023 Airbus, CNES / Airbus, Maxar Technologies, Province of British Columbia, Map data: Google ©2023.

A second key knowledge gap is how characteristics of the adjacent streams shape the utility of riparian areas for terrestrial wildlife. For example, some streams may be too wide or deep to cross, or have steep channel morphologies which could make accessing both the stream and riparian areas difficult for wildlife (Coombes, 2016). Streams with high water velocity or those that frequently flood riparian areas may make some riparian habitat patches too dangerous for certain species. Other wildlife may require upland terrestrial habitat types, referred to in this paper as the matrix habitat type, and infrequently access riparian areas. Streams are also conduits of movement and serve as useful movement corridors for wildlife, especially intermittent streams (Sánchez-Montoya et al., 2016). As water levels are increasingly impacted by climate change, understanding a stream's relative importance to wildlife communities is important for conservation strategies. Thus, to assess whether riparian areas could buffer wildlife from the additional effects of human-caused development and climate change, these knowledge gaps must be addressed.

Here, I used camera traps to survey mammal use of three different habitat types, which I will refer to in this chapter as stream, riparian, and matrix. I surveyed patterns of habitat use along a gradient of development intensity and at various stream orders, accounting for seasonality, visibility distance, and sampling effort. My objective was to understand how development intensity, stream channel morphology, and other landscape features determine how mammalian communities use stream, riparian, and matrix habitat types within watersheds. I hypothesized that:

1) Riparian areas would host a high species richness due to their structural and functional complexity;

2) Some species would have positive associations with riparian areas, because of their traits and/or because development would force mammals towards refugia in riparian habitat patches, however niche partitioning would cause some species to be found in only one of the three habitat types (stream, riparian, and matrix);

3) Development intensity would amplify detections of species who are tolerant of noise and light pollution caused by human activity, but the majority of the mammalian community would have negative associations with development;

4) Mammalian communities would use habitat (of all three types) less frequently around streams with steep streambanks, where habitat around streams with steeper and more challenging channel morphology may restrict access to and movement within streams and riparian areas for terrestrial wildlife, particularly for small mammals;

5) Species would exhibit differences in their associations with elevation, because mammals who avoid development would have positive associations with elevation since development is typically concentrated at lower elevations, while mammals not well adapted to steep topography would have negative associations with elevation, as steeper terrain is more often found at higher elevations;

6) Heavily vegetated habitat patches would be used by herbivores more frequently than lesser vegetated areas; and,

7) Many species (and piscivores in particular) would have higher habitat use near salmon-bearing streams as salmon are a key food source and enrich the surrounding habitat types via nutrient deposition.

2.2. Methods

2.2.1. Study area

I conducted my study in and around Squamish and Maple Ridge, British Columbia between April 20, 2022, and June 16, 2023 (Figure 2.2). Both Squamish and Maple Ridge are secondary cities whose development goals aim to rapidly expand their development footprint (City of Maple Ridge, 2014; District of Squamish, 2022).. However, each city is designed quite differently. Maple Ridge is primarily agriculture and residential zoned, while the city design of Squamish is centered around residential housing and resource extraction (District of Squamish, 2023; *Zoning Bylaw*, 2018). Squamish relies heavily on recreational tourism, as it is a hotspot for hiking, climbing, and mountain biking, and it also experiences high levels of vehicle traffic as people pass through heading northward to access Whistler and Garibaldi Provincial Park (*Tourism Squamish*, 2023). Maple Ridge provides different types of tourist attractions, driven primarily from local agricultural businesses and camping facilities (City of Maple Ridge, 2023).

Both Maple Ridge and Squamish are classified as part of the Coastal Western Hemlock biogeoclimatic zone (British Columbia Ministry of Forests, 2021). Vegetation in this area is tolerant of the mild temperature range and high levels of annual precipitation (Pojar et al., 1991). Dominant species include western hemlock, western red cedar, red alder, bigleaf maple, and Douglas fir (Pojar et al., 1991).

The majority of Maple Ridge is situated at sea level, with the most developed part of the city being adjacent to the Fraser River (Government of British Columbia, 2023; Figure 2.2). Northeast of the Maple Ridge municipality is the University of British Columbia Malcom Knapp Research Forest, Golden Ears Provincial Park, and the Blue Mountain Recreation Site. These forests are the only regions of higher elevation in the city, spanning as high as 1,700 meters (Government of British Columbia, 2023). Squamish is found at the mouth of the Howe Sound (Figure 2.2). The most densely developed sections of the city are found at the lowest elevations, under 50 meters (Government of British Columbia, 2023). Squamish is situated in a valley between two large mountain ranges, Tantalus Range and the Coast Mountain Range. As a result, elevations quickly rise on either side of the city center to reach as high as 2,600 meters (Government of British Columbia, 2023).

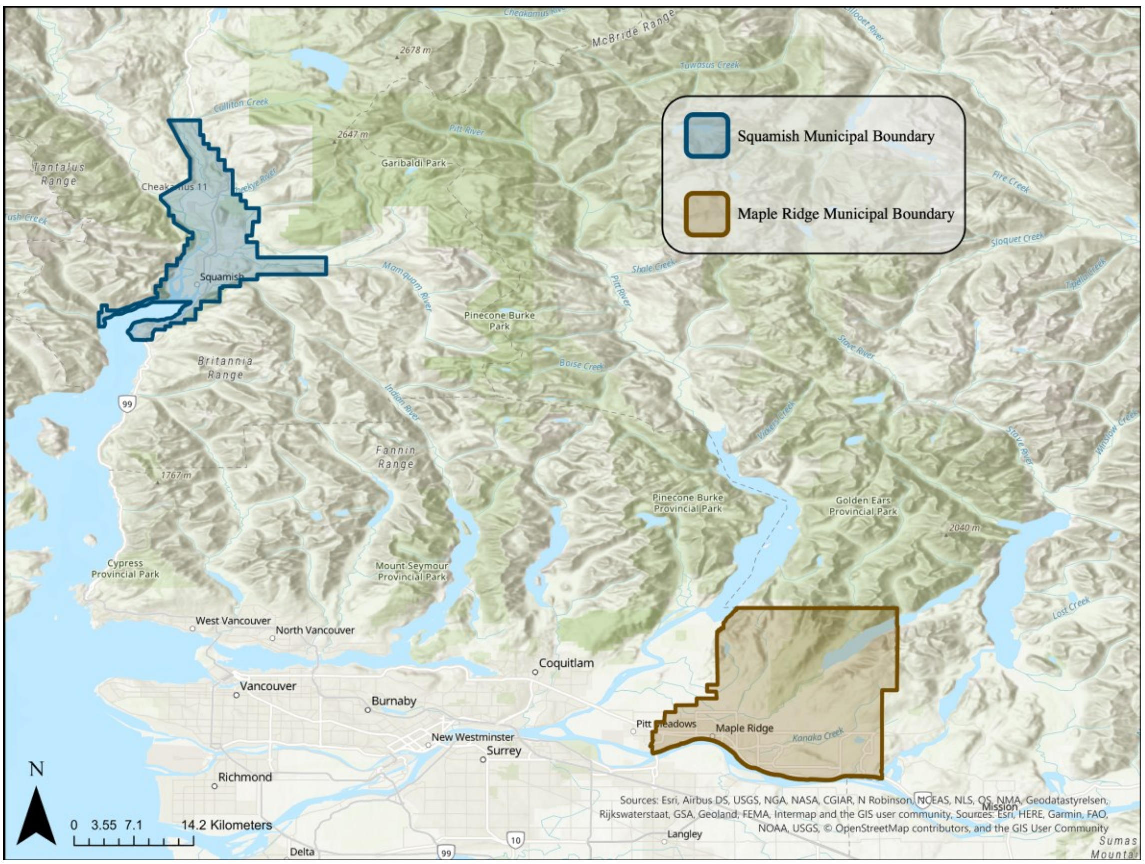

Figure 2.2. Municipal boundaries of Squamish (blue) and Maple Ridge (brown), situated in the Lower Mainland of British Columbia, Canada.
This map was made using imagery from OpenStreetMap (openstreetmap.org/copyright). Contains information licensed under the Open Government License – Maple Ridge (https://opengov.mapleridge.ca/pages/open-government-licence). Contains information licensed under the Open Government License – Squamish (https://squamish.ca/discover-squamish/maps-and-data/open-data/).

I selected these study locations because they represent the major land uses found in British Columbia's Lower Mainland region, aside from the province's largest city, Vancouver (population 631,486; City of Vancouver, 2023). Executing my study in cities as large as Vancouver was not possible as many of the streams were buried during the construction of the city. However, rapid development along the wildland-urban interface is a pertinent issue for biodiversity conservation and the human-wildlife conflict. I believe conducting this study in secondary cities is timely to help city planners develop around priority habitat patches for wildlife.

2.2.2. Camera deployment design

I deployed 72 Reconyx Hyperfire 2 cameras (Reconyx Inc., Holmen, Wisconsin, USA) within my two study locations. I considered the landscape as a gradient extending from the most-developed city center out towards undeveloped natural spaces (Figure 2.3; Figure 2.4). In Squamish, I identified three gradients extending to the east, northeast, and north; in Maple Ridge I identified four gradients running to the west, northwest, north, and east. In each of these landscape gradients, I selected sites at varying distances from the city center and thus in various development types (i.e., urban, residential, agricultural, and undeveloped), and in which I placed cameras. These sites were also chosen at streams with three classifications of width: small, medium, and large. Small streams were designated as those with a Strahler order of one. Medium streams were either second or third order. Larger streams were fourth order or higher. Therefore, the sites within both study locations represented samples of varying development types and stream widths (Table 2.1). Due to logistic site-access constraints and creating gradients of development type and stream size, my camera locations were opportunistically placed. However, I have minimized potential biases in my sampling design by having a large sampling effort and exploring trends in community composition (Cusack et al., 2015). As well, because I explored gradients of development intensity and stream size, and I sampled three different habitat types, my camera trap sites were representative of the greater landscape within each study location (Figure 2.3; Figure 2.4). Specific site selection can be found in more detail in Appendix A.

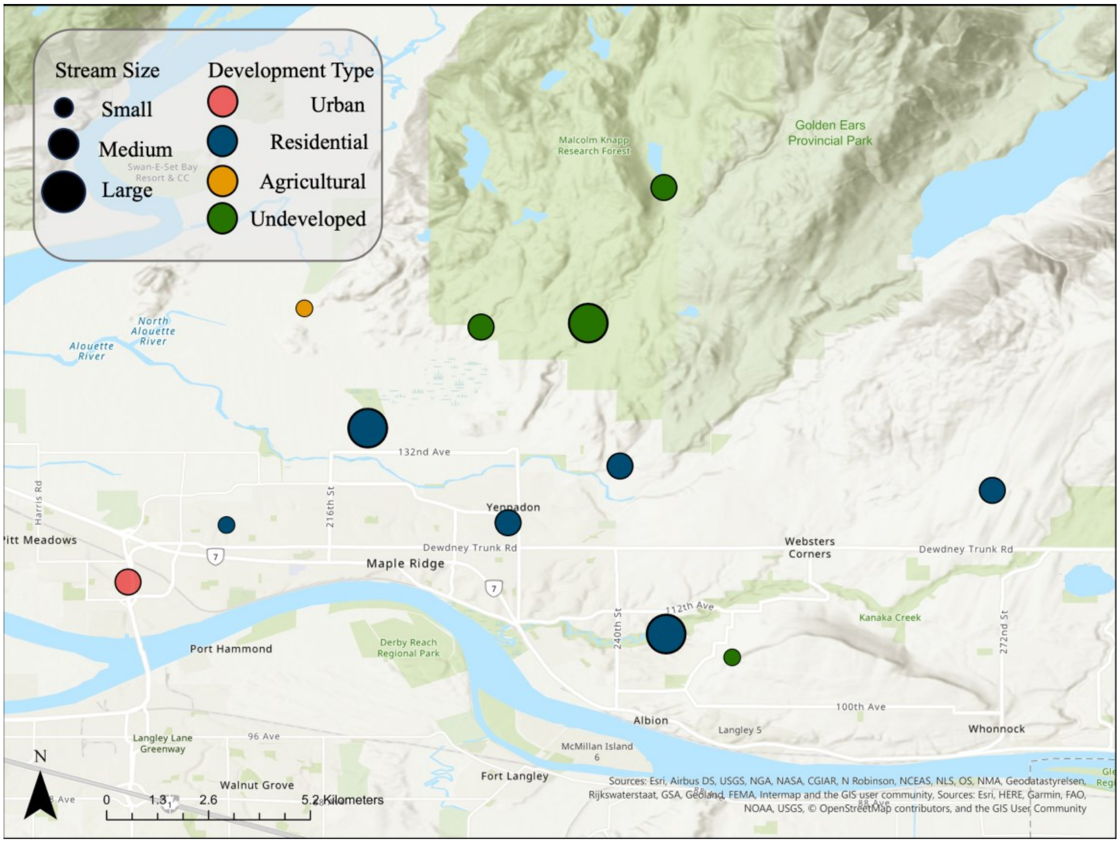

Figure 2.3. Camera trap sites in Maple Ridge extending from the most-developed city center out towards undeveloped natural spaces.

Each site represents three cameras, placed in stream, riparian, and matrix habitat types. The color of the circles represents the development type the groups of cameras were located in. The size of the circles represents the categorical size of the stream the groups of cameras were located nearby. This map was made using imagery from OpenStreetMap (openstreetmap.org/copyright).

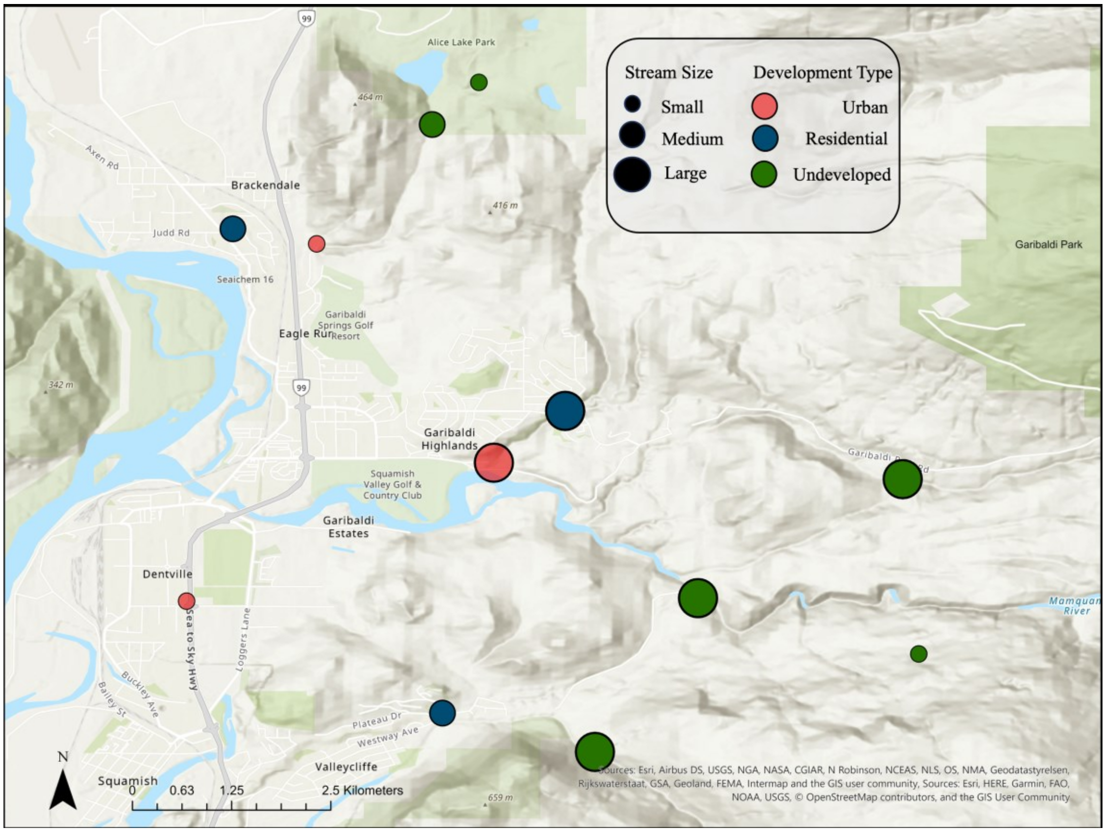

Figure 2.4. Camera trap sites in Squamish extending from the most-developed city center out towards undeveloped natural spaces.
Each site represents three cameras, placed in stream, riparian, and matrix habitat types. The color of the circles represents the development type the groups of cameras were located in. The size of the circles represents the categorical size of the stream the groups of cameras were located nearby. This map was made using imagery from OpenStreetMap (openstreetmap.org/copyright).

Table 2.1. Seventy-two camera trap sites within the two study locations and their associated development type (urban, residential, agriculture, and undeveloped), stream width classification (small, medium, and large), and Strahler order.

Site Name	Development Type	Stream Width	Stream Order
Maple Ridge			
Alder	Residential	Medium	2
Blaney	Undeveloped	Medium	3
Codd	Agriculture	Small	1
Green	Undeveloped	Large	4
Highway	Urban	Medium	2
Hooge	Residential	Medium	2
Kanaka	Residential	Large	4
Marian	Undeveloped	Medium	3
McKenny	Residential	Small	1
Park	Residential	Large	4
Thornvale	Residential/Undeveloped	Small	1
Webster	Residential	Medium	2
Squamish			
Britannia	Urban	Small	1
Dryden	Residential	Medium	2
Edith	Undeveloped	Small	1
FSR	Undeveloped	Small	1
Hop	Urban	Small	1
Jack	Undeveloped	Medium	2
Lower Mashiter	Urban	Large	4
Mamquam	Undeveloped	Large	6
Plateau	Residential	Medium	2
Ring	Undeveloped	Large	4
Stawamus	Undeveloped	Large	4
Upper Mashiter	Residential	Large	4

In total, I installed 72 cameras among 24 sites (Figure 2.3; Figure 2.4). Each site contained a grouping of three cameras, each placed within a 450-meter maximum buffer around an opportunistically selected location along a stream. Camera groupings were spatially autocorrelated because I was gathering an inventory of which mammals used particular habitat types within a site (Rovero et al., 2013). The habitat types in this study were classified as either stream habitat type, riparian area, or any terrestrial space outside the riparian zone, defined as the matrix habitat type. I defined the stream habitat type as the area comprising the stream's bankfull channel width and pointed cameras at the stream channel. I considered the riparian habitat type to begin at the edge of the stream's bankfull channel width and ending when the vegetation changed to deeper forest conditions (less understory vegetation, interior forest trees). I defined matrix as the habitat patch extending from the edge of a riparian area away from the stream.

I followed the WildCAM deployment protocol when standardizing camera settings (Appendix B), installing cameras at my study sites, and collecting data from each camera (Granados & McKeown, 2021). When I arrived at a site, I looked for the best movement path for wildlife. Sometimes there were evident wildlife trails, but if not, I selected flatter locations with open viewsheds. Results from a pilot study indicated that the cameras had a similar detectability whether it was angled along a stream or pointed directly at the stream (Appendix B). Therefore, the stream camera was installed at the edge of the stream and riparian habitat types pointing at the stream channel in the direction that had the clearest view, whether that be pointed upstream, downstream, or directly perpendicular to the length of the stream. It is important to note that the viewshed of my stream cameras included the edge of the stream and the beginning of the riparian area. Consequently, some mammals detected on these cameras were in terrestrial habitat patches. Where I could, I placed the riparian camera facing away from the stream, typically pointing parallel to the stream, capturing the habitat patch alongside the streambank. If this was not possible, I tried to place cameras about 10 meters away from the stream, pointing parallel to the stream. The matrix camera had the largest range of distances from the other habitats. If I could decipher a difference in vegetation between riparian and matrix habitat types (i.e., there was a change from shrubby vegetation to ferns or a sudden opening in the understory), I placed the camera in the matrix vegetation type. However, at most of the sites, the entire undeveloped habitat patch was riparian area. In those instances, I placed the matrix camera as far from the stream as possible within the area (maximum 450 meters as noted above). At my developed sites, I faced the cameras into the developed areas. However, in some cases where I believed humans would tamper with my cameras, I took extra care to conceal the cameras from human view, which meant placing them in the most undeveloped part of the site. In less developed sites, I placed the matrix cameras far from the stream, sometimes up above a berm to get out of the riparian area or out of view from humans on hiking trails.

Camera installation

According to the WildCAM protocol, I installed the cameras between 0.5 to one meter from the ground (Granados & McKeown, 2021), defined in this study as the lowest point the meter stick reached when it was pressed against the target tree and dropped. Where possible, I installed the cameras at 0.7 meters from the ground. This height captured mammals as small as mice to as large as bears in my pilot study. Per the suggestions of WildCAM, I faced cameras north whenever possible, as it reduced the glare from the sun and optimized the photo quality (Granados & McKeown, 2021). However, as this was not always achievable, my primary objective was to angle the cameras either at suspected wildlife trails or in the widest viewshed. More details about the camera installation process can be found in Appendix B.

2.2.3. Habitat patch surveys

Between June 15, 2022, and July 15, 2022, I conducted a thorough vegetation survey and habitat patch assessment at each camera. The habitat patch assessment consisted of qualitative observations of the physical environment surrounding the camera, including the slope of the pitch, the relative density and categories of vegetation (i.e., shrubs, trees, grasses, etc.), proximity to development, and any auditory observations of construction, animal noise, and human noise. I did not use this data in my analysis, but these descriptions were used to learn about the site beyond what a map could tell me.

Hydrological metrics

At stream cameras, I measured variables pertaining to the dimensions of the stream, including measuring the wetted width, bankfull width, streambank height, and depth. I also measured the flow velocity and direction. The wetted width was defined as the width of a segment of a stream where there is contact with water. The bankfull width was the width of the maximum potential of a stream to reach when it is carrying its largest volume of water. The streambank height was a measurement of the vertical distance from the bottom of the streambed to the highest point on the streambank. If the stream was shallow enough to cross, I used a measuring tape to determine the stream's width. If the stream was too wide, fast, or deep to traverse, I used a Laser Rangefinder TruPulse 360R to quantify the stream. I used the Laser Rangefinder for all streambank height measurements. To take this measurement, a field technician stood at one edge of the stream, positioned standing at the bottom of the streambed. Holding the Laser Rangefinder up to eye level, a measurement was taken from the top of the streambank on the opposite side of the stream. The vertical height gathered from this reading was added to the known eye-level height of the field technician if the streambank was taller than the technician. If the vertical height reading was negative, this indicated that the streambank was shorter than the technician and was subtracted from the technician's height. Water depth was measured using a meter stick, inserted vertically into the water until it hit the streambed. The highest point the water touched on the meter stick was recorded as the stream's depth. The flow velocity was calculated using FP111 Flow Probe (Global Water Resources, Phoenix, Arizona, USA). Pointing its turbine downstream and suspending it completely in the water, a reading was generated from the flow meter, which I used to report velocity. I took three different measurements of both water depth and flow velocity, being sure to representatively survey the profile of the stream. For example, I took one measurement from a shallow and fast flowing section, another from a deep and slow-moving section, and a third from a cascade section. Stream flow direction was not measured in the field. Instead, it was determined from a combination of reviewing camera trap data and referencing topographical maps to find output directions downstream.

Tree inventory

Around every camera, I measured a 15-meter radius by extending a tape measure in one direction from the camera trap and pacing a rough circular direction until a quarter of the circle was reached (Figure 2.5). At that point, I remeasured the 15-meter distance and continued this pacing pattern until the whole circle was walked. While I paced the circle, I identified the species and recorded the diameter at breast height (DBH) of every tree inside the buffer around the camera. I performed this survey one time throughout the duration of the data collection period, done during the summer season, and was interpreted as an inventory of the general composition of trees in the forest and a determinant of the overall age of the forest.

Shrub inventory

Similar to the tree inventory, I identified every shrub species within the 15-meter radius around each camera (Figure 2.5). I did not measure the frequency or coverage of shrubs, but rather noted their presence. The shrub inventory was conducted one time to represent the general shrub species composition surrounding each camera.

Quadrats – terrestrial cameras (riparian and matrix)

In addition to the site assessment, I conducted a four-replicate quadrat vegetation survey to quantify the vegetation composition of the habitat patch surrounding the camera, as the types of vegetation could be a determinant of mammal presence at a site (Figure 2.5). To begin, I generated two random numbers, one indicating the direction of movement (0-365 degrees), and the other indicating the distance moved away from the camera in a straight line (1-15 meters). At this position, the one-by-one-meter quadrat was placed on the forest floor, and I examined the habitat patch. I first used a canopy densitometer to collect the average of four estimates of canopy density, pivoting 90 degrees around the center of the quadrat between each replicate. Next, I measured the depth of the duff layer by clearing the leaf litter and digging the meter stick into the organic layer of the soil until the substrate changed to inorganic material. Within the quadrat, I measured the height of the tallest vegetation. The quadrat was divided into a six-by-six grid, so I randomized my starting position by selecting a number between one and six, where one represented the section of the grid closest to the camera and six was the furthest from the camera. I held the quadrat off the ground to not flatten any of the vegetation, and I used a meter stick to measure the vertical height of the tallest woody and herbaceous plant parts that crossed the plane of the meter stick. I excluded trees from this measurement but included shrubs. I repeated this process 5 more times, moving the meter stick directly forward to the next intersection in the quadrat. The last measurement of the quadrat survey was a visual estimation of the percent cover of the following categories: sand, mud, rock, leaf litter (i.e., material fallen on the surface that has not decayed), duff (i.e., organic material that has decayed), bare ground, woody debris, mosses/lichens, graminoids (i.e., grasses, sedges, and rushes), forbs/wildflowers, ferns/allies, shrubs, and seedlings/saplings. All the ground cover categories (i.e., sand, mud, rock, leaf litter, duff, and bare ground) added up to 100 percent. The other categories could exceed 100 percent in total since they could form layers on the terrestrial surface. All measurements of the quadrat survey were repeated three times (Table 2.2).

Table 2.2. A list of all the parameters measured for the quadrat survey at terrestrial sites.

Parameter	Number of Measurements Taken per Quadrat Survey
Canopy cover	4
Height of tallest woody vegetation	6
Height of tallest herbaceous vegetation	6
Depth of duff layer	1
Percent cover sand	1
Percent cover rock	1
Percent cover mud	1
Percent cover leaf litter	1
Percent cover duff	1
Percent cover woody debris	1
Percent cover bare ground	1
Percent cover mosses/lichens	1
Percent cover graminoids	1
Percent cover forbs/wildflowers	1

Percent cover ferns/allies	1
Percent cover shrubs	1
Percent cover seedlings	1

Quadrats - stream cameras

The stream cameras had a four-replicate quadrat survey, however, two of the surveys were conducted in the stream while the other two were conducted on land (Figure 2.5). Similar to the terrestrial quadrat procedure, I began the stream quadrats surveys by generating two random numbers, one for the direction of movement (0 to 180 degrees) and the other for the distance to walk from the camera (1 to 5 meters). The direction of movement was no more than 180 degrees to ensure that I would survey in the stream and not on land. The movement distance from the camera did not exceed five meters because most streams were between two and 10 meters, with the widest stream reaching 23 meters. If the width of the stream was less than five meters, I adjusted the randomized distance where the maximum distance was the nearest meter less than the bankfull width. Starting from the right side of the camera as you face it, a technician turned to the right until the randomized number of degrees was added to the original orientation. Once arrived at the quadrat location, the quadrat was held over the water and I estimated a percent cover of the following categories: impermeable surface, rocks (diameter greater than 20 centimeters), gravel (diameter between 2.5 to 20 centimeters), fine gravel (diameter less than 2.5 centimeters), sand, mud, living plants, leaf litter, biofilm, and woody debris. The streambed categories (i.e., impermeable surface, rocks, gravel, fine gravel, sand, and mud) summed to 100 percent. The other categories could exceed 100 percent in total as they could layer in the water. Canopy cover estimates were recorded following the same procedure as at the terrestrial sites, while standing in the middle of where the quadrat was placed in the stream. This process was repeated one time before completing two terrestrial quadrat surveys. The terrestrial quadrat surveys followed the same protocol outlined in the previous section, including recording measurements for the canopy cover, duff depth, height of the tallest vegetation, and the percent cover of land cover categories. The final step was to record the overall stream morphology, selected among the following categories: cascade, step-pool, plane-bed, pool-riffle, and dune ripple.

I repeated the habitat patch assessment and stream and terrestrial quadrat surveys three times, between October 17, 2022, and November 23, 2022, for the fall season, between February 14, 2023, and March 21 for the winter season, and between May 9, 2023, and May 17, 2023, for the spring season. During the winter and spring seasons of field work, I reintroduced the hydrological metrics, including measuring the stream's wetted width, bankfull width, streambank height, and three measurements of both stream depth and flow.

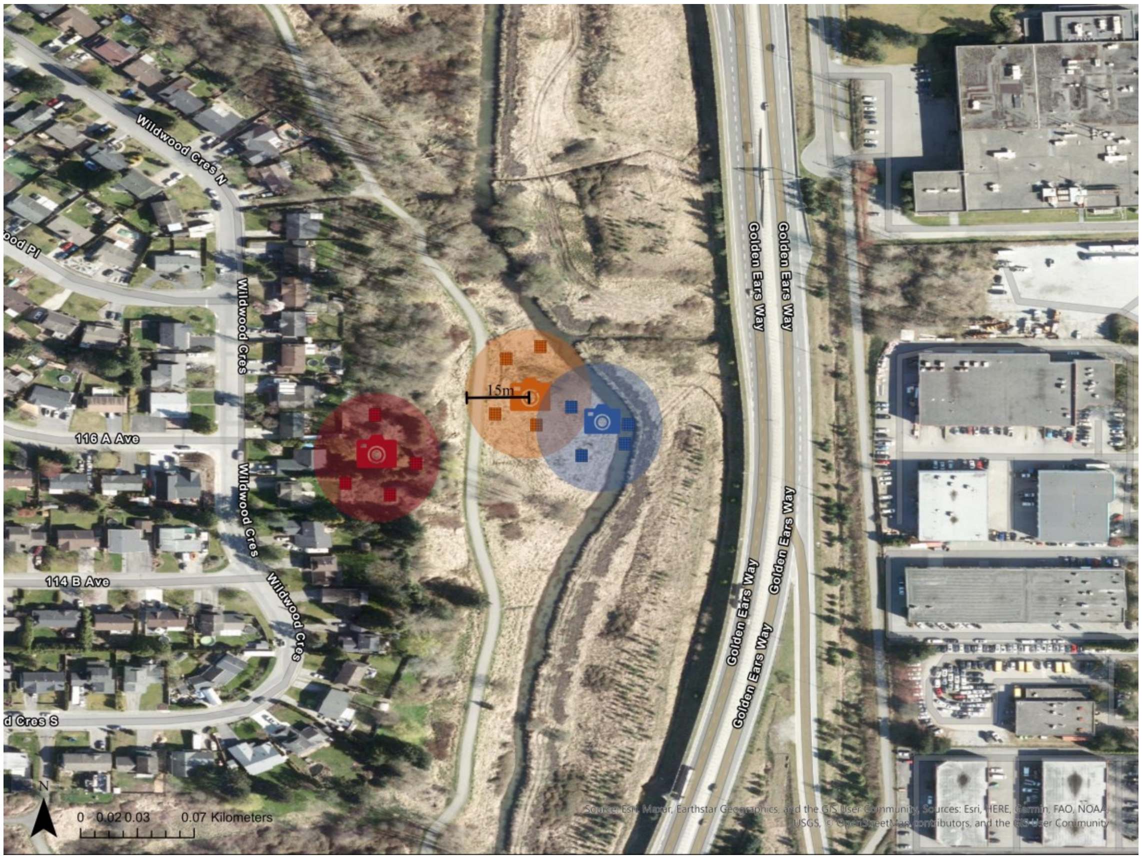

Figure 2.5. Camera trap set-up from the "Highway" site in Maple Ridge. The blue camera was placed in the stream habitat type, the orange camera was placed in the riparian habitat type, and the red camera was placed in the matrix habitat type. The circles around each camera represents the 15-meter radius buffer in which I conducted tree, shrub, and quadrat surveys and are color-coded according to the camera's habitat type. The color-coded squares represent a sample of where I placed randomized terrestrial and stream quadrats. This map was made using imagery from OpenStreetMap (openstreetmap.org/copyright).

Visibility distance qualification

My research methodology produced a potential bias in detectability. Given that I sampled in three different habitat types and across a gradient of development intensity, visibility distances were not uniform despite my efforts to trim vegetation surrounding the camera. Therefore, in the field I attempted to quantify the camera's visibility as a means to control for a detectability bias that could occur between camera traps. To do this, a field technician positioned the Laser Rangefinder at the camera's height and in line with the direction it was pointing. The longest visible distance directly in front of the camera was measured, which I define in this report as visibility distance. The visibility was deemed obstructed if there were significant barriers in the viewshed, such as rock walls, dense vegetation, or large logs.

The visibility distance estimation was initially measured in the fall 2022 (between October 17, 2022, and November 23, 2022) and was repeated in the winter 2023 (between February 14, 2023, and March 21, 2023), because I hypothesized that the visibility distance would change when deciduous vegetation dropped its leaves. I repeated the visibility distance measurement again in spring 2023 (between May 9, 2023, and May 17, 2023) to see how the cameras' visibility were affected by the regrowth of deciduous vegetation.

2.2.4. Camera trap battery and memory card replacement

Throughout the surveying period from April 2022 to June 2023, I checked the cameras seasonally to ensure they were functioning properly. The seasonal visits occurred in July 2022, August 2022, October/November 2022, February/March 2023, and June 2023. All batteries were replaced, and memory cards were changed. I never partially replaced batteries, so in cases where I lacked enough batteries to do a complete replacement, I left the used batteries in the camera and returned later with fresh batteries. I did not remove the cameras from the tree while checking them, rather, I loosened the strapping enough to open the camera and work from its original position. After equipment replacement, I returned the cameras to their original position. Occasionally, I adjusted the angle or height of the camera to better capture mammal movement, or to protect the camera from destruction. In a few instances, I moved the cameras altogether to a better location, however, I maintained that their new position be within the 15-meter radius from the previous location. In one case, I needed to move the camera beyond the 15-meter radius of the previous location, but this was due to vandalization. My manual adjustments were considered new deployments, so I measured the visibility distance at each new camera position to account for changes in detection probability (Moll et al., 2020). If the cameras were compromised in any way (i.e., vandalized or malfunctioning), I replaced the camera with a Bushnell Core DS Low Glow camera while the Reconyx camera was being fixed (Appendix B). Once the Reconyx was returned, I replaced it back in the field. Only one camera could not be replaced, so I left a Bushnell Core DS Low Glow camera in the field for the duration of the survey period.

2.2.5. Camera trap retrieval

Between June 5, 2023, and June 16, 2023, I collected all cameras from the field. In the field, I noted if there were any abnormalities of the camera functionality or at the surrounding site.

2.2.6. Photo identification

I began classifying photo data after I collected memory cards at the end of the summer. I used Wildlife Insights (Ahumada et al., 2020), an online cloud-based data management platform for camera trap research, to process all photo data per the suggestion of WildCAM. Wildlife Insights had an easy image uploading process, remote working capabilities for my photo identification team, and ensured privacy standards could be met for photos that contained humans. Personnel working on photo identification were trained using a manual to ensure standardized methods and decision-making (Appendix C). Each photo received the same identification within a burst, even if what was in the photo changed. I identified to the species level whenever possible, however, if the animal was indecipherable, I identified to the taxonomic level at which I could be confident. Each identification reported the species of the animal(s), the highest number of individuals in any one photo, and the associated behavior(s) and direction(s) of movement. In cases where there were two different species in the photo, each photo in the burst received an individual identification for each species.

2.2.7. Data processing

Photo data processing

I downloaded classified photo data from Wildlife Insights, excluding blank images and images containing humans. I performed all analyses in R v. 4.2.1 (R Core Team, 2022), and explored the data as per Beirne (2023). I checked the data for any errors, matched mammal detections with site and deployment data, mapped the study sites, and produced several outputs, including overall independent (30-minute threshold to remove multiple detections of the same individual; Sollmann, 2018) mammal detections and detections at monthly, weekly, and daily temporal scales, a camera trap locations reference table, and a list of all the mammals I found at my cameras.

Environmental covariate extraction

I prepared a list of variables which may influence the mammal detections observed on my camera traps. The data came from a combination of field data collection and extraction from databases via RStudio and Google Earth Engine. A complete list of covariates and details about how they were collected for this analysis and from what source can be found in Appendix B. With compiled covariate data, I generated a correlation table to determine if any variables should be condensed or eliminated due to collinearity. I excluded variables yielding a value of $r > 0.7$ or $r < -0.7$ from the pairwise Pearson correlation coefficient. The environmental variables included in the final analysis are displayed in Table 2.3.

Table 2.3. Environmental predictor covariates used in the joint species distribution models with associated means and ranges for each study location and habitat type.

A detailed description of how the variables were measured can be found in Appendix B. Variables not reported from a specific season were averaged across seasons and the mean in this table was expressed as the average of those seasonal means, but the range represents the true spread among seasons. The channel morphology variables were taken from the stream habitat type, so were only reported in the stream columns for each study location (and the other habitat types were replaced with "NA"). The recorded salmon presence variable was reported as the mean number of sites which had salmon-bearing streams plus the range and was only reported in the stream columns for each study location (and the other habitat types were replaced with "NA"). The season and habitat type categories were both categorical variables.

Variable	Maple Ridge Matrix (n = 12)	Maple Ridge Riparian (n = 12)	Maple Ridge Stream (n = 12)	Squamish Matrix (n = 12)	Squamish Riparian (n = 12)	Squamish Stream (n = 12)
Development Intensity Category						
Distance to nearest road (meters)	42.20 (3.21 - 101.75)	60.09 (12.02 - 143.21)	59.25 (8.03 - 169.60)	41.66 (14.48 - 70.25)	41.54 (13.17 - 79.36)	42.42 (4.60 - 79.79)
Channel Morphology Category						
Summer streambank height (meters)	NA	NA	1.36 (0.25 - 2.51)	NA	NA	2.09 (0.21 - 6.31)
Landscape Features Category						

Maximum NDVI	7594.46 (4086 - 9458)	7791.73 (5133 - 9723)	7641.35 (5133 - 9723)	7705.04 (3920 - 9790)	7788.31 (3231 - 9820)	7825.65 (3231 - 9792)
Elevation (meters)	82.69 (5 - 316)	82 (3 - 312)	78.38 (4 - 311)	138.33 (13 - 445)	132.58 (13 - 442)	132.08 (13 - 438)
Recorded salmon presence	NA	NA	11	NA	NA	8
Camera Category						
Average maximum visibility distance (meters)	11.06 (0 – 25)	8.62 (4.5 – 15.3)	9.77 (0 – 36)	10.20 (4 – 22)	9.1 (3.6 – 23.4)	13.22 (4.4 – 29.6)
Camera-days (sampling efforts)	400 (351 – 423)	390.50 (307 – 421)	387.42 (258 – 421)	397.67 (326 – 420)	394.33 (316 – 420)	401.58 (385 – 420)
Season Category (spring, summer, fall, winter)						
Habitat Type Category (matrix, riparian, stream)						

Species traits covariate extraction

I collected a series of species traits variables, including home range, body mass, and diet preferences to answer my hypotheses about how channel morphology would impact smaller-sized mammals and how seasonal events, like salmon migrations, would impact the mammalian community's use of riparian areas. Most of the trait data came from EltonTraits 1.0 (Wilman et al., 2014). Any missing information was filled in using the Animal Diversity Web database (University of Michigan, 2020). A list of all species traits variables and a more detailed description of how data were obtained can be found in Appendix B. I log-transformed body mass so it could be used as a proxy for metabolic rate since it scales with body mass. Differences between species and available resources within a landscape might permit different levels of movement (LaBarbera, 1989), thus the need to create a standard metabolic rate. With the compiled species traits data, I generated a correlation table, similar to my environmental covariates, to refine my list and eliminate correlated variables. I excluded variables yielding a value of $r > 0.7$ or $r < -0.7$. The trait variables included in the final analysis are displayed in Table 2.4.

Table 2.4. Species traits covariates used in the joint species distribution models with associated means and ranges from all study locations and habitat types.

A detailed description of the variables and how they were measured can be found in Appendix B.

Variable	Mean (Range)
Log-transformed body mass (grams)	7.94 (4.78 - 12.32)
Fish diet (percent)	6.15 (0 - 90)
Seed diet (percent)	6.50 (0 - 50)
Other plant material diet (percent)	14.75 (0 - 100)

2.2.8. Statistical analysis

I used the Hierarchical Modelling of Species Community (HMSC) Bayesian joint species distribution model (JDSM) package v. 3.0-13 in R v. 4.2.1 (Ovaskainen et al., 2017; R Core Team 2022) to analyze count data of mammal detections at my camera traps and test my hypotheses about the effects of development intensity, channel morphology, and other landscape features on mammal habitat use. I chose to use a joint species distribution model because this modeling framework can simultaneously examine the relative effect of environmental covariates, species traits covariates, and species interactions on mammal detections. I did not explicitly address potential issues of imperfect detections; however, I took care to standardize detection probability in the field by having a large sample size and effort, standardizing my camera trap model, and placing cameras 0.5 – one meter off the ground (Kays et al., 2020). In my joint species distribution model, I excluded species with low detections, included visibility distance to attempt to standardize the cameras' viewsheds, and I reported changes in habitat use within each species rather than between species, which would introduce biases related to body size, movement range, or activity pattern (Burton et al., 2015). Due to the number of observations in my dataset, it was not possible to include all potential explanatory variables in the joint species distribution model. Based on exclusion of collinear variables and priori hypotheses, I selected variables which belonged to six categories: development intensity, channel morphology, landscape features, camera, season, and habitat type. I used the distance to the nearest road to represent my development intensity category. My channel morphology variable was the summer streambank height. Landscape features variables were elevation, recorded salmon presence, and maximum NDVI. Camera-specific variables were average maximum visibility distance and sampling effort (camera trap days). Season was broken down into four-month periods corresponding to the fall, winter, spring, and summer. Finally, I included three habitat types (stream, riparian, and matrix). I also included two random effects of camera trap site (that is, the grouping of three cameras at a given site) and study location (Squamish and Maple Ridge). I used default priors (0.5 when probability = 0) and modeled mammal detections with a Poisson distribution. I ran 3 Markov chain Monte Carlo (MCMC) chains with 325,000 iterations, a burn-in period of 25,000 iterations, and thinned to every 300th sample to yield posterior samples of 1000 for inferences. I evaluated MCMC convergence by a combination of visually confirming chain mixing in MCMC trace plots and evaluating both effective sample size and the potential scale reduction factor (PSRF). I assessed overall model fit by calculating the model's explanatory power for each species with pseudo-R^2 and a cumulative average root mean squared error (RMSE; Ovaskainen et al., 2017). To address the relative importance of different variable types I first determined if all variables used in the model were significantly influencing mammal detection counts by extracting 95% credible intervals for each variable and observing if they overlapped zero. Then I used variance partitioning to explore how covariate groupings (development intensity, channel morphology, landscape features, camera, season, and habitat type) and random effects (site and study location) impacted mammal habitat use.

Model selection

Using the Bayesian framework detailed above, I fit three models for comparison (Figure 2.6), which would help me determine how development intensity, channel morphology, and other landscape features would impact mammal detections among my sites. The first model was a mixed-variable model containing environmental covariates from the development intensity category, the channel morphology category, and the landscape features category (Table 2.3). The second model contained environmental covariates from the development intensity and landscape features categories (Table 2.3). The third model contained environmental covariates from the channel morphology and landscape features categories (Table 2.3). In all models, I also included habitat type and controlled for season, maximum camera visibility distance averaged across deployments, and sampling effort (camera-days). Lastly, I included species traits variables in each model, which consisted of log-transformed body mass and diet preferences (fish, seeds, and plants; Table 2.4). I selected taxa to be included in my models by running the mixed-variable model with all taxa and removing mammals that had poor convergence. I removed 12 taxa from the joint species distribution models due to poor convergence. Those mammals were short-tailed weasel, elk, martens, northern flying squirrel, long-tailed weasel, cougar, red fox, nutria/muskrat, striped skunk, chipmunks, American beaver, and western spotted skunk (scientific names in Table 2.5). I applied the same models to all taxa. I ran the three models and assessed model fit as described above.

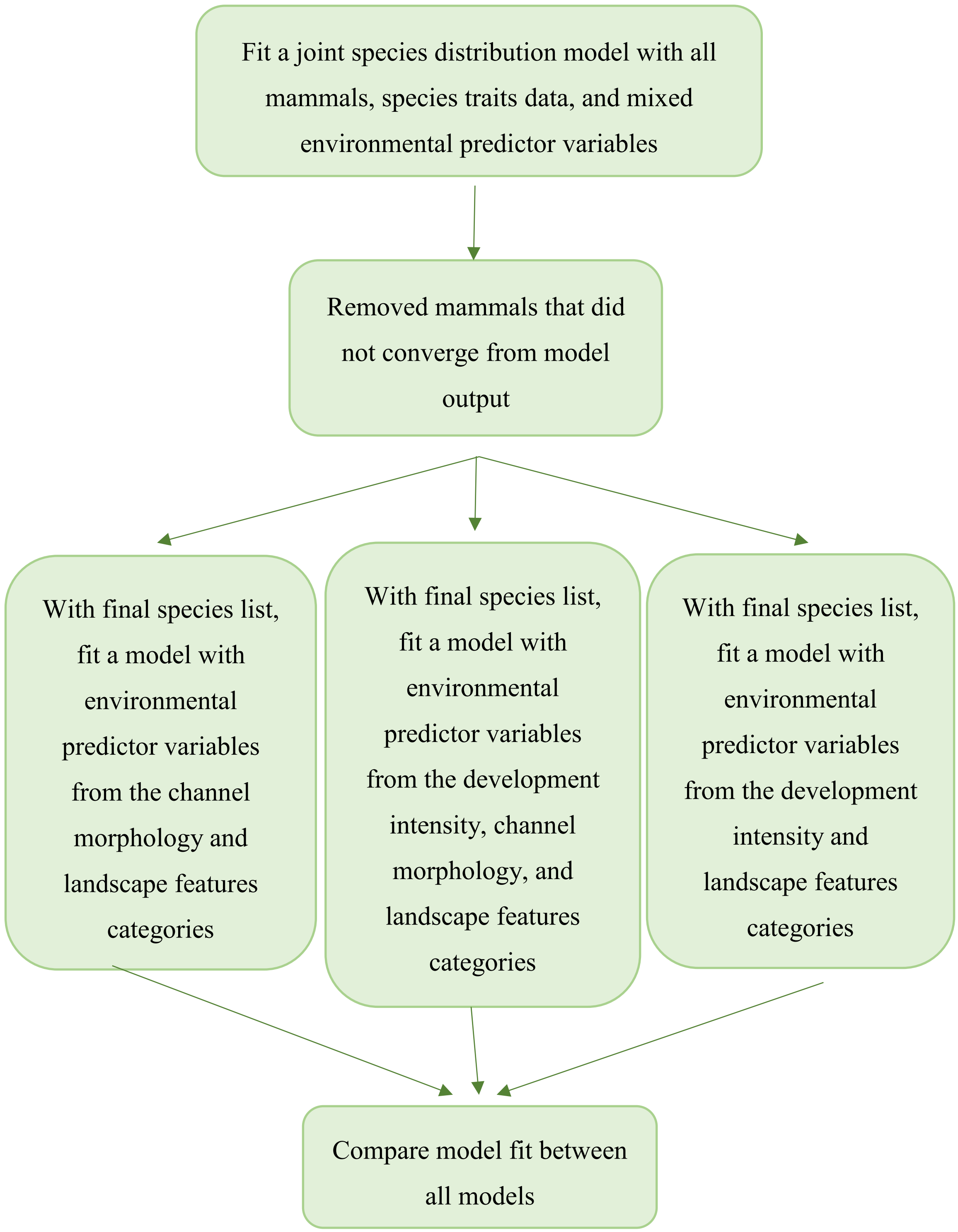

Figure 2.6. **A flowchart outlining the process of assembling three joint species distribution models and comparing model fit.**

2.3. Results

With a total sampling effort of 28,464 camera-days, I obtained 61,278 images belonging to 7,917 independent detections (i.e., 30-minute periods designed to remove multiple detections of the same individual) of mammals (Appendix D). Total detections were highest during the fall season, with a sharp drop in detections throughout the winter season before gradually increasing in the spring and summer (Figure 2.7). Mammal observations spanned 25 different taxonomic groups, of which I identified 20 to the species level (Table 2.5). I found 22 taxa in Squamish and 24 taxa in Maple Ridge. Western spotted skunk was unique to Squamish and elk, red fox, and nutria/muskrat were unique to Maple Ridge (scientific names in Table 2.5).

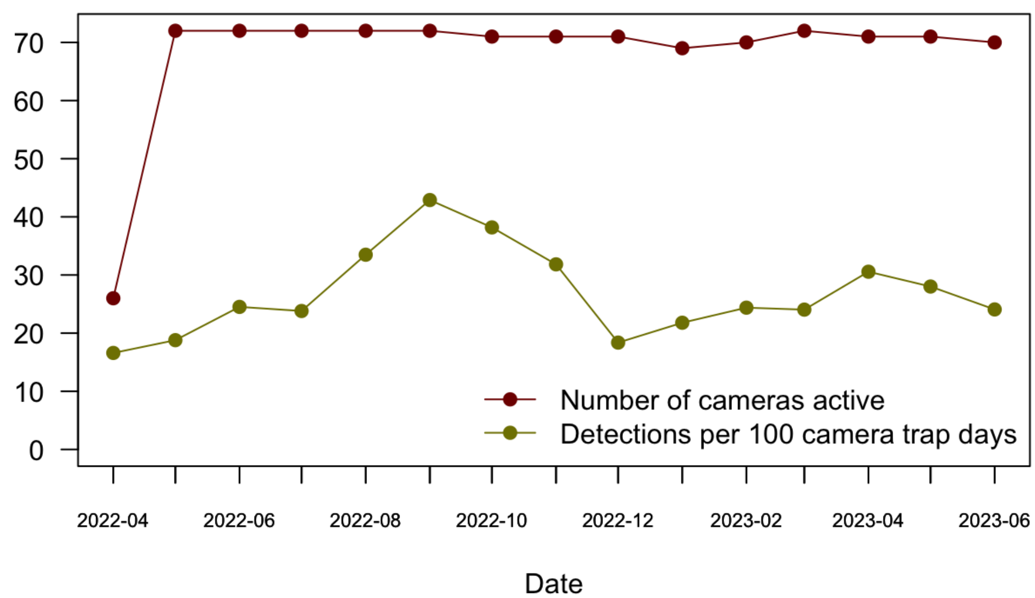

Figure 2.7. Seasonal detections across the total survey period.
The green line represents mammal detections standardized per 100 camera trap days with dots indicating detection rates at the corresponding month. The red line shows the number of cameras active during they survey period with dots indicating the number of active cameras at the corresponding month.

Table 2.5. Mammals detected during the survey period.

Captures refer to the number of independent events in which the taxonomic group was detected on my cameras, assuming perfect detections. Captures have been further broken down to reflect independent detections per habitat type.

Taxonomic Group	Total Captures	Matrix Captures	Riparian Captures	Stream Captures
Gray squirrel (*Sciurus spp.*)	2541	1091	951	499
Rats and mice (*Rodentia*)	1347	178	331	838
Northern raccoon (*Procyon lotor*)	1259	220	206	833
Coyote (*Canis latrans*)	686	343	200	143
American black bear (*Ursus americanus*)	535	193	220	122
Mule deer (*Odocoileus hemionus*)	403	225	102	76
Douglas's squirrel (*Tamiasciurus douglasii*)	321	116	164	41
Domestic dog (*Canis familiaris*)	237	86	33	118
Snowshoe hare (*Lepus americanus*)	165	149	13	3
Bobcat (*Lynx rufus*)	128	46	39	43
Domestic cat (*Felis catus*)	92	40	47	5
American mink (*Neogale vison*)	43	1	18	24
North American river otter (*Lontra canadensis*)	40	2	3	35
Striped skunk (*Mephitis mephitis*)	26	11	8	7
Nutria (*Myocastor coypus*) or Muskrat (*Ondatra zibethicus*)	24	0	0	24
American beaver (*Castor canadensis*)	21	5	9	7
Chipmunks (*Neotamias spp.*)	16	4	12	0
Short-tailed weasel (*Mustela erminea*)	7	0	7	0
Elk (*Cervus canadensis*)	7	0	7	0
Martens (*Martes spp.*)	4	3	1	0

Northern flying squirrel (*Glaucomys sabrinus*)	4	0	3	1
Long-tailed weasel (*Neogale frenata*)	3	0	1	2
Cougar (*Puma concolor*)	3	0	0	3
Red fox (*Vulpes vulpes*)	2	0	2	0
Western spotted skunk (*Spilogale gracilis*)	2	0	2	0

To test my first hypothesis that riparian areas would host a high species richness, I looked specifically at the number of unique mammals I found on my cameras in riparian areas. Of the mammals I detected, 23 taxa were present in the riparian habitat type, 19 taxa were in the stream habitat type, and 17 taxa were in the matrix habitat type. Because of imperfect detection and differences in detectability across species and habitat types, I did not perform statistical inference on species richness, and here present qualitative results only. Due to my opportunistic sampling design and the nature of camera trap research, there is a probability that I did not detect all species that were present on my cameras or in the surrounding area. The species accumulation curves in Figures 2.8 and 2.9 provide an estimate of the overall species richness captured on my cameras based on my sampling effort. The aggregate species richness shown in Figure 2.8 indicates adequate sampling due to the taper of the curve. Broken up into the three habitat types reveals a potential need for further sampling in the stream habitat type, but the matrix and riparian habitat types were adequately sampled (Figure 2.9). To test my second hypothesis that niche partitioning would cause specialization to one habitat type, I generated a Venn diagram displaying in which habitat type(s) I detected each mammal. Not all mammals were found in every habitat type. Mammals found exclusively in one habitat type belonged to those I excluded from my joint species distribution model due to low detections and poor convergence, and so therefore I could not parse apart whether these results were due to habitat specialization or low detectability. Cougar and nutria/muskrat were found only in stream habitat patches and elk, western spotted skunk, red fox, and short-tailed weasel were found in riparian areas, and 15 species were found in all three habitat types (Figure 2.10).

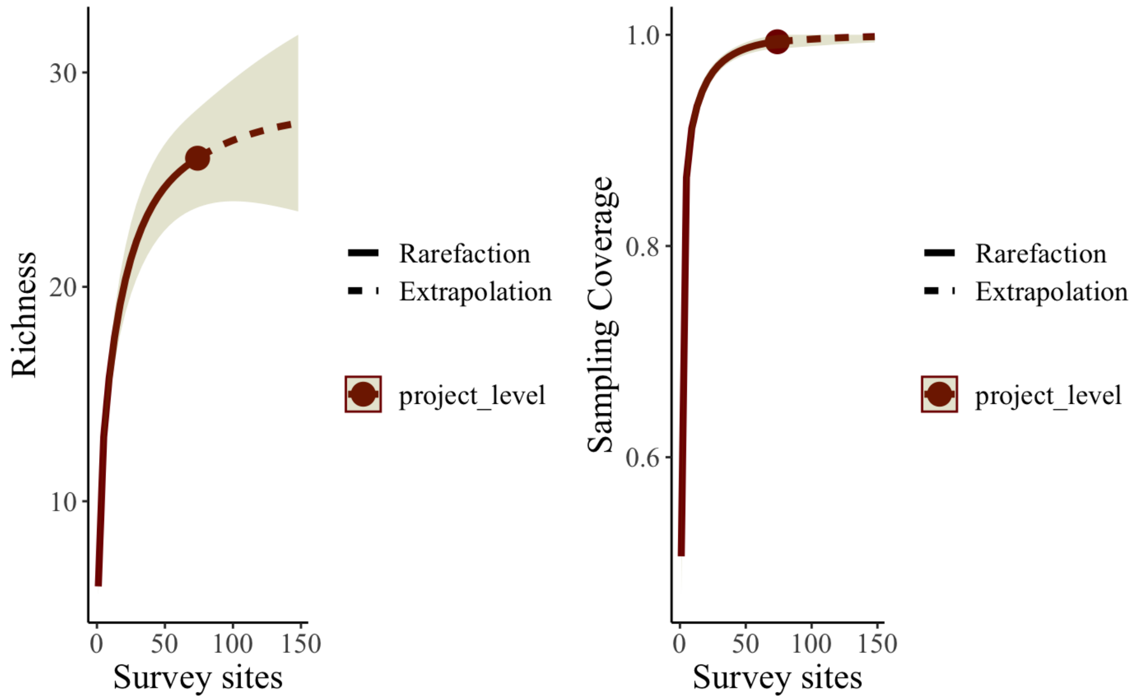

Figure 2.8. Sampling effort curves displaying species richness (left) and sample coverage (right) across survey sites.
Both curves aggregate total sampling effort from the duration of the survey period. Aggregate richness and sample coverage displayed a taper in their respective sampling effort curves. The solid red line indicates how many species I observed. The dotted line extrapolates trends in richness should I have increased my sampling effort, highlighting potential species I might have missed due to my sampling design. The green buffer around the red line is a 95% confidence interval.

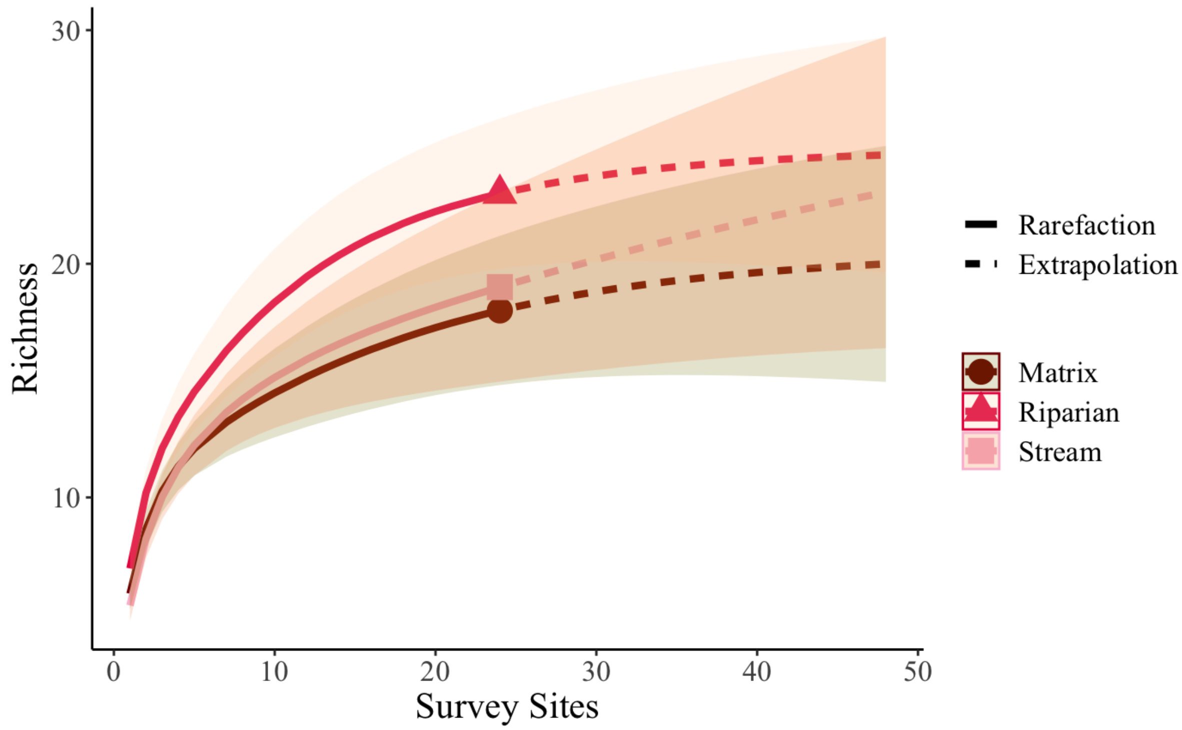

Figure 2.9. Sampling effort curves displaying species richness for each habitat type across survey sites.

All curves aggregate total sampling effort from the duration of the survey period. Aggregate richness for each habitat type displayed a taper in their respective sampling effort curves. The solid lines indicate how many species I observed. The dotted line extrapolates trends in richness should I have increased my sampling effort, highlighting potential species I might have missed due to my sampling design. The shaded buffers around the lines are 95% confidence intervals.

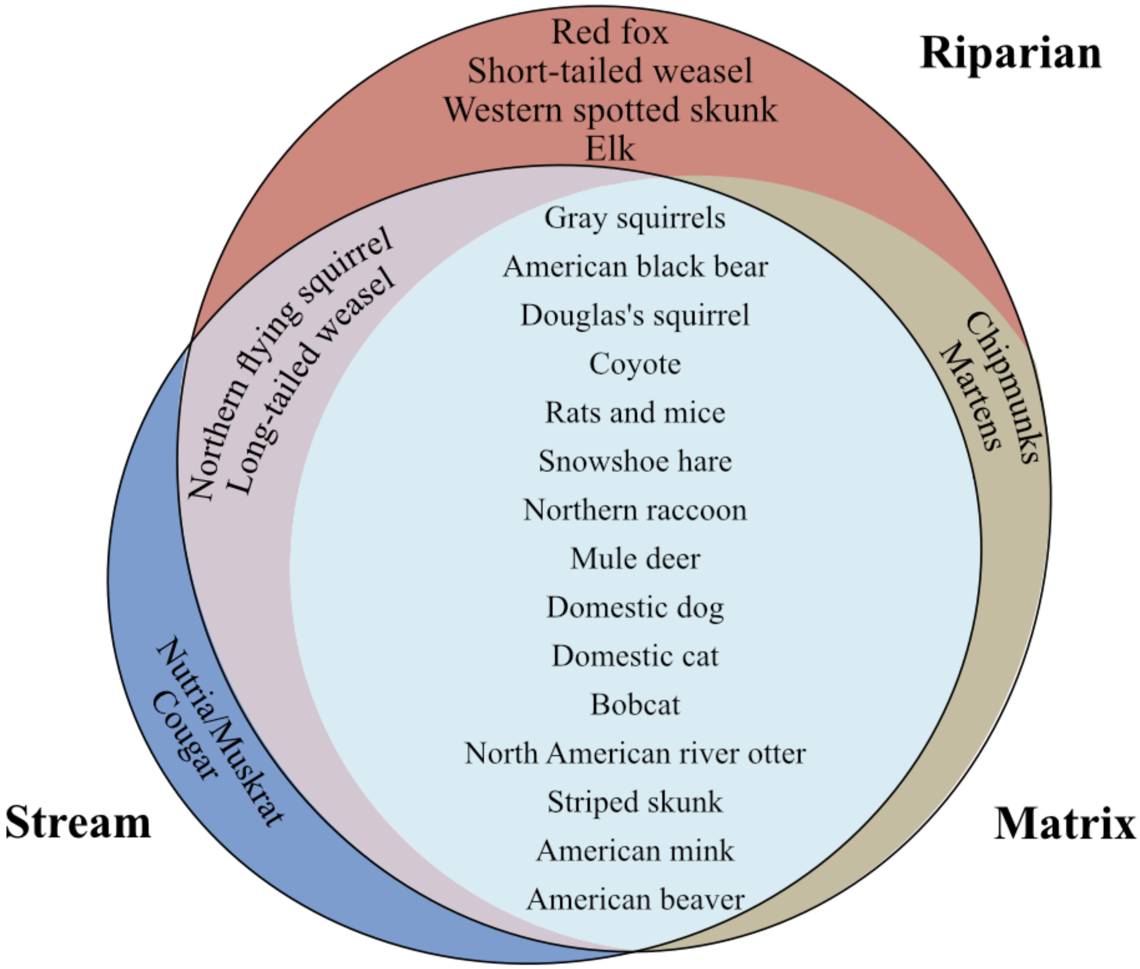

Figure 2.10. A Venn diagram showing at which habitat types I found each mammal.

2.3.1. Role of development intensity, channel morphology, and landscape features in shaping communities

To test my second though seventh hypotheses that mammals would have divergent responses to development intensity channel morphology, and landscape features, I used joint species distribution models to assess associations among species, their traits, and their environments.

In total, I included 13 mammals representing 7,797 detections in my analysis. The mixed-variable model had the best fit when compared to the channel morphology and development intensity models. The mixed-variable model had the lowest average RMSE (RMSE = 4.29), followed by the development intensity model (RMSE = 4.32) and the channel morphology model (RMSE = 4.51). The fixed and random effects together in the mixed-variable model explained 73.1% of total variation in mammal detections (Figure 2.12), while the channel morphology model explained 71.4% and the development intensity model explained 70.7%. While all models explain a large majority of the variation, my results indicate that both development intensity and channel morphology are important to mammal detections, and each contribute in slightly different ways. Therefore, I present only the results of the mixed-variable model. Across the mammal species included in this model, this model produced a mean pseudo-R^2 of 0.34 (Appendix F), however the model was species-specific in how well it was able to explain detections. The model was best able to explain the detections of domestic cat (pseudo-R^2 = 0.64) and the least able to explain detections of American mink (pseudo-R^2 = 0.06; Figure 2.11).

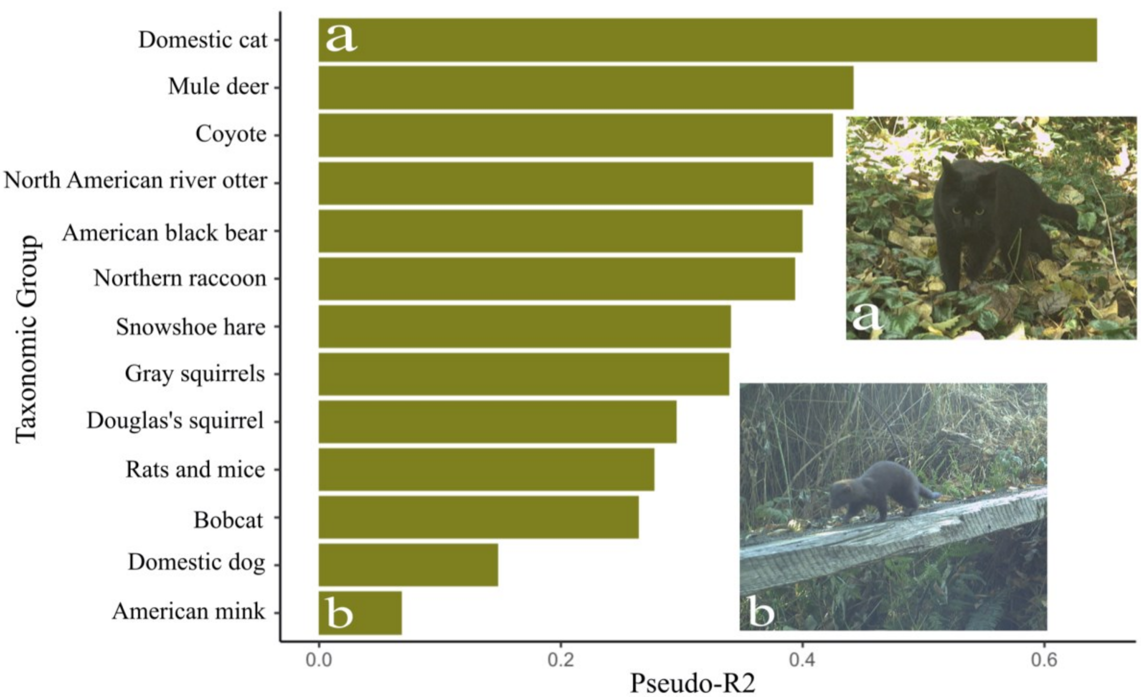

Figure 2.11. Ranked pseudo-R^2 values for the taxonomic groups included in the mixed-variable joint species distribution model.

To further test my second through seventh hypotheses, I partitioned the variance from the mixed-variable model to see how different environmental predictor variables explained the variance in detections of each taxonomic group. Across all taxa, elevation explained the most variation in detections at 27% (Figure 2.12). Development intensity explained 16.7% of the variation. Salmon presence explained 5.8% of the variation, and maximum NDVI explained 3.7%. Only 0.9% of the variation was explained by stream channel morphology. Camera, season, and habitat type categories explained low portions of the variation (10.8%, 5.3%, and 3% respectively). Random effects accounted for a total of 26.9% of the variation, with the majority explained by the camera trap site (i.e., groupings of cameras in the three different habitat types).

The environmental predictor variables explained different portions of the variance in detections for each mammal. Development intensity explained the most variation for American beaver, American black bear and American mink (Figure 2.12). Elevation was most important for coyote, mule deer, domestic cat, Northern raccoon, and rats and mice.

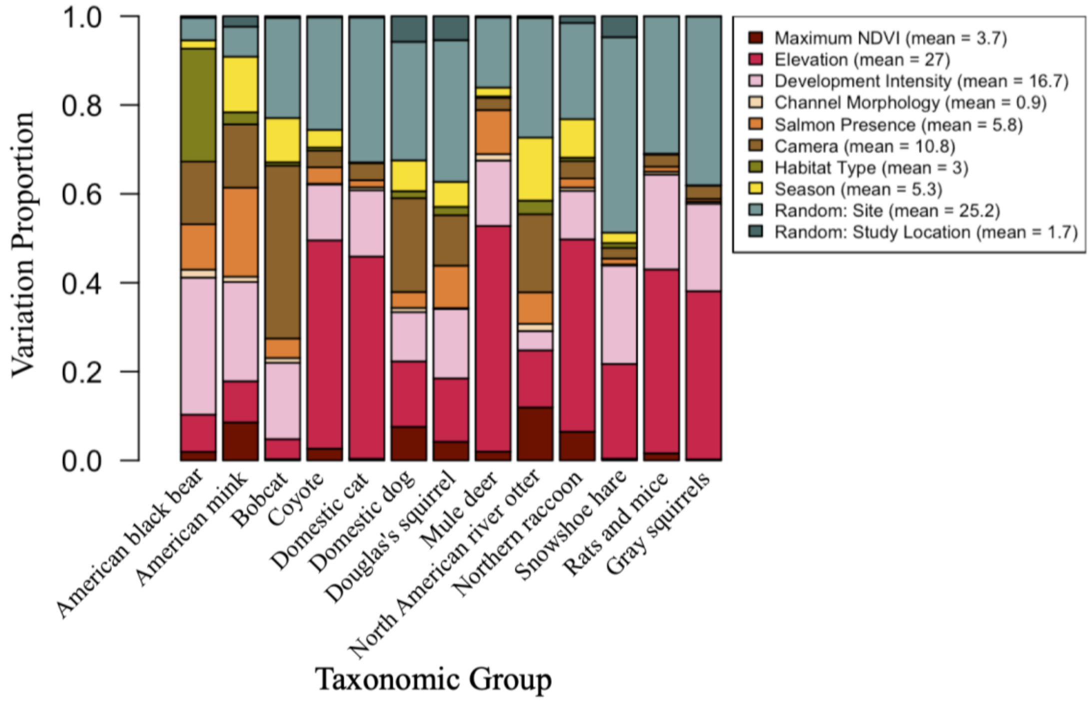

Figure 2.12. Proportions of the total variance explained by the model (73.1%) explained by random effects and categories of environmental predictor variables used in the mixed-variable joint species distribution model.
This variance was further broken down to show how each grouping of environmental predictor variables explained the variance per species. Distance from the nearest road represents the development intensity category; summer streambank height represents the channel morphology category; recorded salmon presence, maximum NDVI, and elevation comprise the landscape features category; average maximum visibility distance and sampling effort (camera-days) make up the camera category; matrix, riparian, and stream habitat types make up the habitat type category; and the season category consists of fall, winter, spring, and summer seasons. I also included variance explained by random effects. "Random: Site" represents the grouping of camera traps at a site. "Random: Study Location" represents the study location (i.e., Maple Ridge or Squamish).

To test my hypotheses about how development intensity, channel morphology, and other landscape features shaped how the mammalian community used habitat, and my second hypothesis that more species would have positive associations with riparian areas, I examined posterior distributions of associated mammalian species and environmental predictor variables.

Mammals responded differently to each of the environmental predictor variables, as noted from the 95% credible intervals (Appendix G). After considering the effect of all other environmental covariates, American black bear, mule deer, and northern raccoon showed positive associations with road distance, while rats and mice and gray squirrels had negative associations (Figure 2.13).

While stream channel morphology did not explain a large portion of the variance in this model, several species had strong directional associations with this variable. Rats and mice, North American river otter, Douglas's squirrel, and American mink were detected at higher rates in areas with high streambanks after accounting for other covariates (Figure 2.13). American black bear and mule deer were negatively related to higher streambanks.

In addition to the hypothesized and detected effects of development intensity and channel morphology, the other landscape features I tested were important in explaining the detections of some species (Figure 2.13). Gray squirrels, rats and mice, northern raccoon, Douglas's squirrel, domestic cat, and coyote had negative associations with maximum NDVI, while mule deer was the only species to have a positive association. Gray squirrels, rats and mice, snowshoe hare, Douglas's squirrel, and domestic cat were positively related with elevation, while northern raccoon, bobcat, and American black bear were negatively related. Salmon presence had seven positive associations, belonging to American black bear, bobcat, domestic cat, domestic dog, Douglas's squirrel, rats and mice, and gray squirrels. North American river otter had a negative association with salmon presence.

Some species had either positive or negative associations with specific habitat types (Figure 2.13). American black bear and domestic cat were detected at higher rates in riparian areas, while gray squirrels, snowshoe hare, and northern raccoon were detected at lower rates in riparian areas. Gray squirrels, northern raccoon, North American river otter, and American mink were detected at higher rates in stream habitat patches, while American black bear, coyote, Douglas's squirrel, snowshoe hare, and mule deer were detected at lower rates.

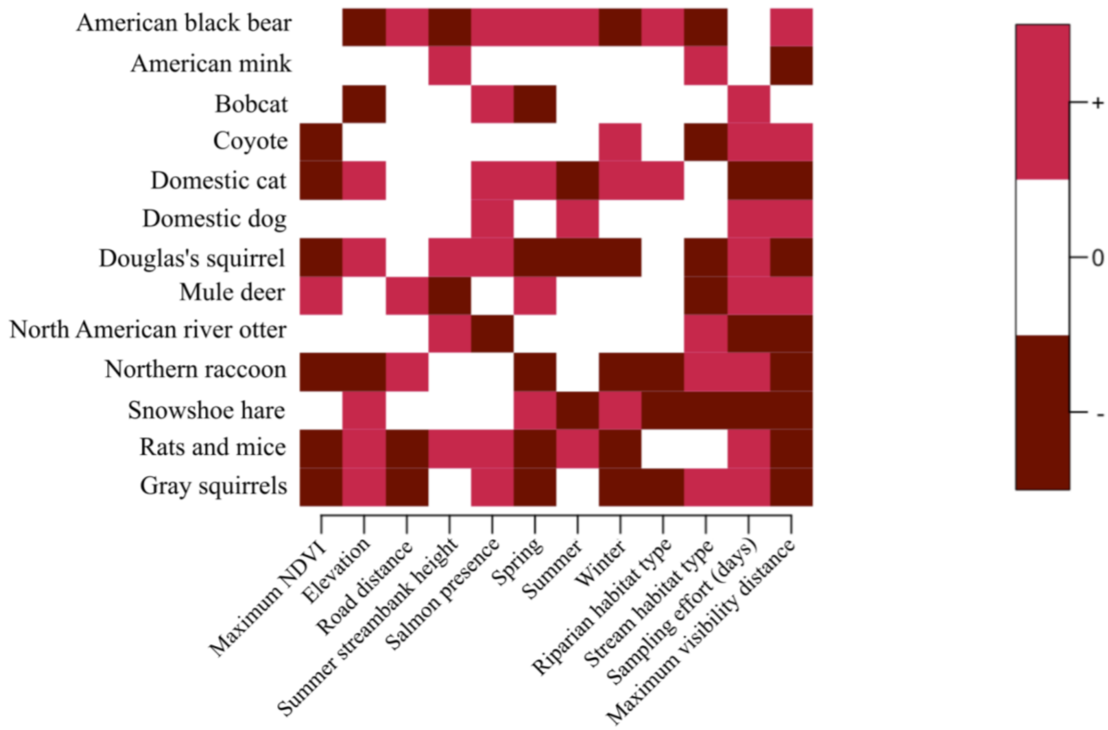

Figure 2.13. Species-specific responses to environmental predictor variables included in the joint species distribution model.
This plot shows posterior support levels of > 95%. Positive association is indicated in pink, negative association is dark red, and no strong association is white.

2.3.2. Species traits variables

To test my fourth hypothesis that smaller mammals would have more difficulty navigating steeper streambanks, my sixth hypothesis that herbivores would use more heavily vegetated habitat patches, and my seventh hypothesis that piscivores would use habitat patches near salmon-bearing streams, I used the mixed-variable joint species distribution model to assess associations among species traits and environmental predictor variables. I found that body size had no strong association with streambank height but had positive associations with the spring and summer seasons and a negative association with elevation (Figure 2.14). Mammals with a plant diet had no strong association with maximum NDVI but did have a positive association with the spring season and a negative association with the stream habitat type (Figure 2.14). Herbivores with a seed diet had a negative association with maximum NDVI (Figure 2.14). I found that piscivores had a positive association with salmon presence (Figure 2.14).

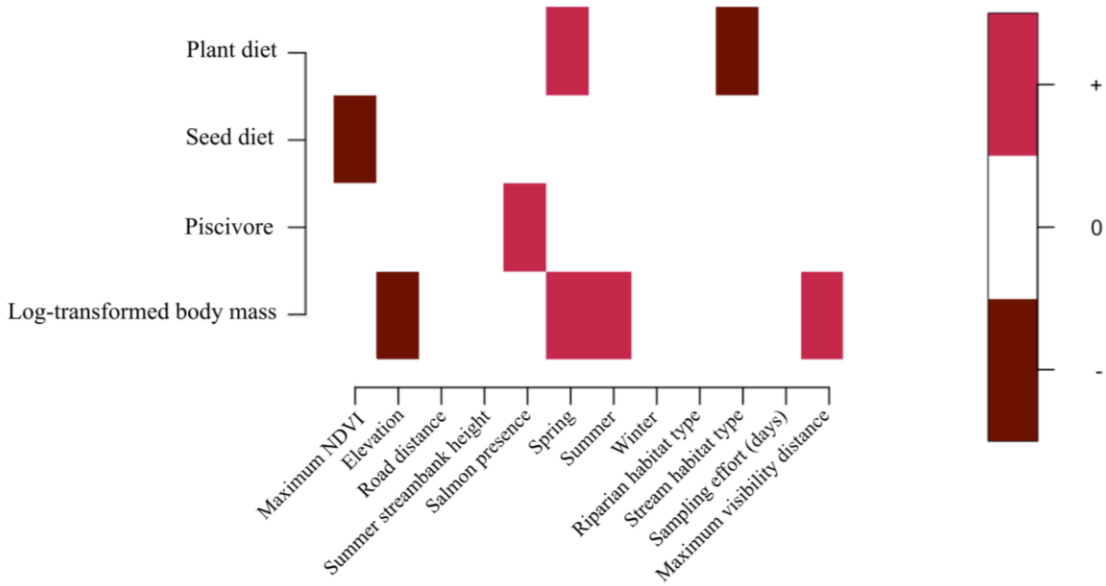

Figure 2.14. Species traits responses to environmental predictor variables included in the joint species distribution model.
This plot shows posterior support levels of > 95%. Positive association is indicated in pink, negative association is dark red, and no strong association is white.

I further examined my seventh hypothesis and plotted standardized detection data of all mammals who had positive associations with salmon presence in sites where salmon were present and sites where they were absent to see if this relationship varied seasonally (Figure 2.15). Since I did not have an equal number of sites where salmon were present and absent, I reported the data as detections per 100 camera trap days. Sites with salmon recorded the highest detections in the summer and the lowest detections in the winter. Sites without salmon had the highest detections in the fall and lowest detections in the winter.

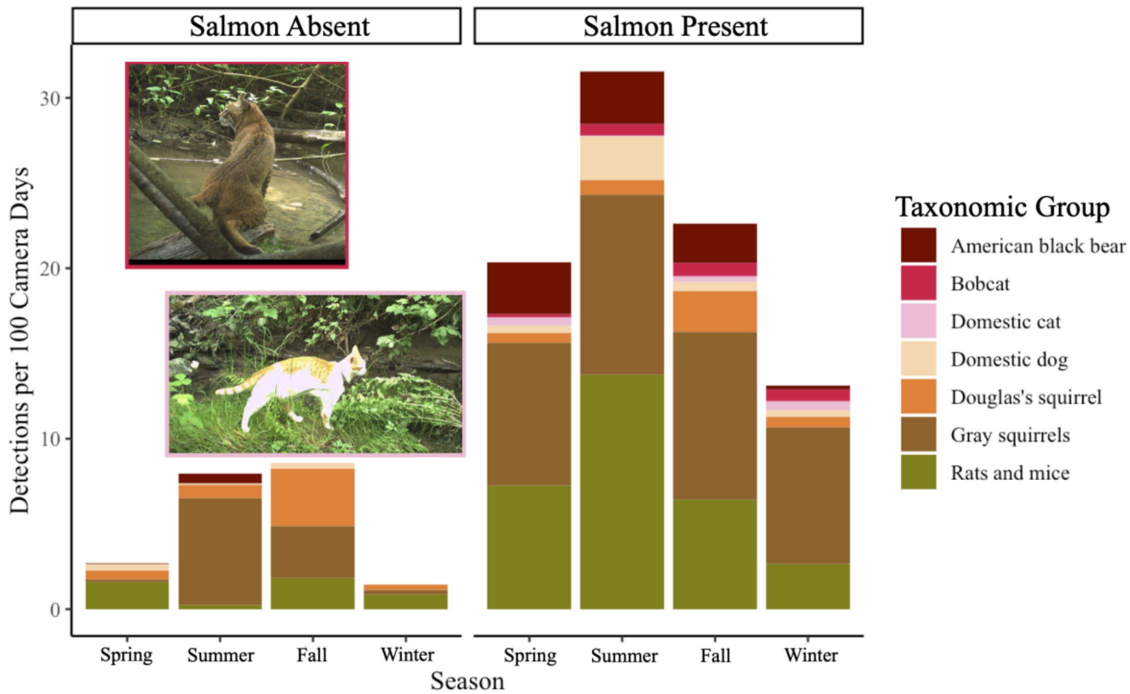

Figure 2.15. Detections per 100 camera-days for seven taxa who were positively associated with salmon presence based on the results from my joint species distribution model.

Detections were reported from riparian and stream cameras and were broken up into sites that had recorded salmon presence (n = 57; right) and sites that did not have recorded salmon presence (n = 15; left). The two photos depict the two piscivores included in the model (upper photo = bobcat; lower photo = domestic cat).

Table 2.6. Summary of my hypotheses and main findings from my results.

Hypothesis	Finding
Riparian areas would host a high species richness due to their structural and functional complexity.	I found 23 unique mammals using riparian areas out of the 25 mammal species detected across all habitat types. Thus, this represents 92% of the species detected in this study.
Some species would have positive associations with riparian areas, because of their traits and/or because development would force mammals towards refugia in riparian habitat patches, however niche partitioning would cause some species to be found in only one of the three habitat types (stream, riparian, and matrix).	Only two mammals were positively associated with riparian areas after considering the effect of all other environmental predictor variables. Six species were found exclusively in one habitat type.
Development intensity would amplify detections of species who are tolerant of noise and light pollution caused by human activity, but the majority of the mammalian community would have negative associations with development.	Higher detections of rats and mice and gray squirrels near roads. Fewer detections of northern raccoon, mule deer, and American black bear near roads.
Mammalian communities would use habitat (of all three types) less frequently around streams with steep streambanks, where habitat around streams with steeper and more challenging channel morphology may restrict access to and movement within streams and riparian areas for terrestrial wildlife, particularly for small mammals	Six of the mammal taxa detected in this study had associations with streambank height. The species with positive associations were generally smaller (American mink, North American river otter, Douglas's squirrel, and rats and mice) and the species with negative associations were generally larger (mule deer and American black bear). Body size had no strong associations with streambank height.

Species would exhibit differences in their associations with elevation, because mammals who avoid development would have positive associations with elevation since development is typically concentrated at lower elevations, while mammals not well adapted to steep topography would have negative associations with elevation, as steeper terrain is more often found at higher elevations.	No mammal who was positively associated with development intensity (i.e., negatively associated with road distance) was also positively associated with elevation. Gray squirrels, snowshoe hare, rats and mice, Douglas's squirrels, and domestic cats had positive associations with elevation, while American black bear, bobcat, and northern racoon had negative associations with elevation.
Heavily vegetated habitat patches would be used by herbivores more frequently than lesser vegetated areas.	Mammals with a plant diet had no strong association with maximum NDVI while mammals with a seed diet had a negative association.
Many species (and piscivores in particular) would have higher habitat use near salmon-bearing streams as salmon are a key food source and enrich the surrounding habitat types via nutrient deposition.	More than half of the mammal taxa detected in this study showed positive associations with salmon presence. Piscivores also were detected in higher frequencies near salmon-bearing streams.

2.4. Discussion

Understanding habitat use by mammalian communities is becoming increasingly important for conservation strategies as the rise of human-caused development and climate change are rapidly altering habitat suitability. This study used camera traps and joint species distribution models to evaluate the relative impact of development intensity and stream channel morphology on habitat use by mammalian communities in Squamish and Maple Ridge, British Columbia. This study revealed several important findings pertaining to my hypotheses. First, riparian areas in my study locations host a high diversity of mammals and are an important part of the landscape mosaic, but maintaining connectivity to other habitat types is critical because many of the same species move through multiple habitat types. Second, mammalian communities include species with different associations to development intensity, channel morphology, and other landscape features, illuminating that conservation strategies need to be both landscape-specific and species-specific.

2.4.1. Riparian areas are an important habitat type for mammals

My cameras detected 23 different mammals using riparian areas across the gradient of development intensity and stream channel morphologies. These mammals represented diverse guilds, including seed dispersers, grazers, hunters, scavengers, and movers of nutrients from the aquatic to terrestrial habitat types. While localized environmental variables may deem certain riparian areas less suitable than others for particular species, at the landscape scale, riparian areas were used by mammals of a variety of functional groups. This signifies that despite their small area, riparian areas provide a diversity of resources and environmental conditions for different mammal species. While only two species had positive associations with riparian areas, habitat loss and fragmentation from human development will continue to eliminate available undeveloped space (particularly in the matrix habitat type), which could force mammals towards the remaining intact riparian areas. Therefore, improving habitat-level resilience among riparian areas should be a conservation priority. The explanatory power of development intensity was high across all mammal species, which would suggest that development is a strong indicator of habitat use, with some species having negative associations with increased levels of development. Therefore, the continued loss and degradation of riparian areas could result in the loss of critical functional groups at these habitat patches.

Many of the species which used riparian areas also used at least one of the other two habitat types. Riparian areas feature habitat characteristics of both stream and matrix habitat types; however, some species may require specific resources found exclusively in stream (i.e., fish; Levi et al., 2015) or matrix (i.e., interior forest conditions; Pereboom et al., 2008) habitat types. As ecotones, riparian areas maintain local connections between stream and matrix habitat types, and this connectivity stretches throughout a landscape because of their dendritic properties (Campbell Grant et al., 2007). Local connectivity between stream, riparian, and matrix habitat types may be especially important for species with small home ranges who cannot move great distances to access suitable habitat. Species that use riparian areas and move between matrix and stream habitat types will introduce resource exchanges among the three habitat types. These exchanges of resources and organisms improve the value of local habitat patches for other wildlife.

As the crux of the connection between matrix and stream habitat types, riparian areas facilitate many physical and biological processes that occur in all three habitat types. Riparian and matrix (to a lesser extent) habitat types receive water, nutrient, and sediment depositions from streams, which nourish the vegetation that grows in these habitat patches (Naiman et al., 2005a). Streams receive vegetation and debris inputs (Trevarrow & Arismendi, 2022; Wohl, 2017a), which provide food and shelter for aquatic organisms, and riparian vegetation stabilize stream channels (Braudrick et al., 2009; Langendoen et al., 2009). Together, all of these processes improve the health of local habitat patches (Bieger et al., 2019; Cederholm et al., 1999; Kautza & Sullivan, 2016).

Scale is also an important factor to consider with regards to mammal use of riparian areas. Many of the mammals I detected on my cameras are wide-ranging and were captured in all three habitat types and across the development gradient. As well, the explanatory power of the random effect at the camera trap site (i.e., grouping of three habitat types) was high, which could indicate that many species do not partition their activity so finely into these three habitat types, or that they need to cross multiple habitat types to reach required resources. Buffers are one management strategy which could shelter wildlife from the negative effects of development and climate change and could optimize riparian function and capacity to host a high species richness and diversity. The optimal size of these buffers is species-specific (Bodie, 2001; Semlitsch & Bodie, 2003; Spackman & Hughes, 1995). Although there is some understanding of the ideal buffer width for certain species, many management plans neglect these requirements on account of making a “one-size-fits-all” buffer (Lee et al., 2004). Therefore, it is urgent to improve management plans to include buffers that can support ecological communities as development and climate change intensify.

2.4.2. Development intensity, channel morphology, and landscape features highlight a need for multi-scale management strategies

Environmental characteristics had varying effects on species within the mammalian community. Across all species, elevation and development intensity had high explanatory power, while salmon presence, maximum NDVI, and channel morphology had lower explanatory power. Therefore, at the landscape scale, elevation and development intensity are highly indicative of habitat use. Elevation is often associated with other landscape variables, such as distance from development, steepness, temperature, and vegetation composition (Krosby et al., 2018; Moradi et al., 2020), all of which describe habitats which mammals must select to match their resource and environmental condition requirements. The complexity of this variable could suggest why it had the highest explanatory power for the mammalian community. The effects of the distance to the nearest road, a metric of development are becoming more apparent as habitat loss is eliminating available space and resources for mammal use and fragmentation is altering environmental conditions and connectivity throughout a landscape (Sih et al., 2000). Salmon presence, maximum NDVI, and channel morphology had less explanatory power than elevation and development intensity at the community level, which indicates that these variables are several among a broad range of environmental characteristics influencing mammalian communities.

Some species had strong associations with different environmental characteristics, regardless of the importance of those environmental characteristics at the community level. Referencing my third hypothesis, I expected development intensity would amplify detections of species who were tolerant of anthropogenic noise and light pollution, but that the majority of the mammalian community would have negative associations with development. I found that rats and mice and gray squirrels were negatively associated with road distance, therefore positively associated with development intensity. These taxa are common dwellers of high development areas (Bonnington et al., 2014; Feng & Himsworth, 2014), so these results support my hypothesis. While not the majority of the mammalian community, I found that American black bear, mule deer, and northern raccoon were detected further from roads. Mule deer and American black bear are sensitive to noise pollution from roads and urban activity (Collins et al., 2022; Ditmer et al., 2018), and particularly large or busy roads present movement barriers for northern raccoon (Prange et al., 2004). However, these species were also all present in more developed sites. Habitat choice is complex, and habitat use by these three mammals could be driven by other variables (those included in the model or ones not included) in concert with development intensity. However, a species like northern raccoon, who is an opportunistic scavenger and common resident of urban areas (Bozek et al., 2007), might be able to live amongst human development (where we could not place cameras due to human privacy concerns) to access food sources. Strong urban raccoon populations have a small home range because anthropogenic sources provide adequate food (Prange et al., 2004). This could be part of the reason why northern raccoon was negatively associated with riparian areas. Perhaps other species who are tolerant of human development may enter these areas to find food, but may not want to live within the infrastructure, so seek riparian areas as residential habitat to stay in proximity to development or movement corridors into and out of developed spaces. American black bear could be one such species, as it had a positive association with riparian areas.

Based on my fourth hypothesis, I expected that mammalian communities would not use habitat of all three types around streams with steep streambanks. Only two species were negatively related to steep channel morphology, which does not support my hypothesis, and instead suggests that the steepness of the streambed does not necessarily restrict access to surrounding habitat types. However, mule deer and American black bear were negatively associated with steep streambanks. Hooved animals, like mule deer, may have difficulty navigating steep and rocky substrate. Bears might be drawn towards more intermediate or shallow streambanks, where there is easy access to fish. As well, flooding of salmon-bearing streams and the spread of salmon carcasses in terrestrial habitat patches enhances nutrient availability for terrestrial vegetation (Ben-David et al., 1998). Since American black bear had a positive association with salmon-bearing streams, this variable may be strongly influencing habitat use. I also hypothesized that smaller mammals would have difficulty accessing streams with steep streambanks. Contrary to my hypothesis, I found that body size was not indicative of how challenging channel steepness is for mammal species, however, this could be due to two reasons. First, I excluded 12 species from my model due to low detections and poor model convergence. Many of those species had small body sizes. Future research incorporating a more representative dataset of the mammals detected in stream habitats is needed to disentangle the relationship between body size and stream channel steepness. Second, some of the smaller and medium-sized mammals, like the American mink and the North American river otter, had positive associations with channel morphology. These mammals are semi-aquatic and are adapted to survive near streams. This may give them an advantage when navigating steep streambanks (Holland et al., 2019).

I expected from my fifth hypothesis that mammals who avoided development would have positive associations with elevation. My results do not support my hypothesis. American black bear and northern raccoon, two of the road avoidant species were negatively associated with elevation. Gray squirrels and rats and mice, two taxa who were detected at higher rates in more developed areas, had positive associations with elevation. Many of the higher elevation sites we selected were accessed via logging roads. Proximity to the noise pollution from large logging trucks may deter road-avoidant species like American black bear and northern raccoon from these higher-elevation sites. I also expected that mammals not well adapted to steep topography would have negative associations with elevation. My hypothesis is again not supported. I found that bobcats had a negative association with elevation even though they select steep and rocky denning sites (Donovan et al., 2011). This is likely because there are other environmental characteristics that bobcats seek for survival, such as vegetation composition or prey availability (such as the northern raccoon which also had a negative association with elevation; Tewes et al., 2002). My study did not survey in any high alpine ranges, so future research surveying along a wider elevation gradient might elucidate both a pattern of high elevation habitat use because of lowland development and the effect of steepness on habitat selection.

My sixth hypothesis stated that heavily vegetated habitat patches would be used by herbivores more frequently than lesser vegetated areas. I found that 50 percent of mammal species and specifically mammals with a seed diet had negative associations with maximum NDVI. This variable does not specify vegetation composition, so vegetation is likely still an important variable for many mammals, including herbivores, but additional research is needed to investigate how the composition is influencing habitat use. I collected data on vegetation composition but did not include it in the joint species distribution model due to limitations of sample size and correlation among potential explanatory variables. However, when I examined the vegetation data for ten sites with the highest NDVI values it showed that these sites were forested areas dominated by western hemlock. Primary shrub species included ferns, salmonberries, and huckleberries, though much of the understory was composed of woody debris and duff. This provides a potential explanation for why so many species had negative associations with maximum NDVI because having a mostly open understory leaves little foraging opportunities for ground-dwelling mammals. Ungulates prefer to browse on western hemlocks, which could explain why mule deer was the only species to have a positive association with maximum NDVI (Burney & Jacobs, 2011).

Based on my seventh hypothesis, I expected that many species, especially piscivores, would use habitat types near salmon-bearing streams. My hypothesis is supported as I found that over 50 percent of the mammals included in my model were positively associated with salmon presence despite it having low explanatory power at the community level. Salmon are an important food source for many wildlife, and their nutrient subsidies to terrestrial habitats are important to the health of terrestrial vegetation (Hilderbrand et al., 2004). Managers looking to identify priority habitat patches for wildlife should consider the importance of salmon-bearing streams for terrestrial wildlife. Managers should also consider the implications of salmon lost from a part of the watershed due to environmental degradation and the cascading effect on available food sources for wildlife and nutrient revitalization for terrestrial habitat patches.

2.4.3. Limitations of camera trap research

Camera trap research is an ever-evolving science, and there are some limitations from my study that must be addressed. While I did capture bursts of three photos per detection, sometimes the animal passed too quickly through the camera's field of view or was only detected in a small portion of the viewshed. As a result, without adequate confidence in the animals' classifications, I was not able to include all detections in my analysis. Due to the same issues, I was not confident enough to identify all mammals to the species level. In some cases, two species could not be distinguished, such as with rats and mice, so I had to group them into higher orders. While I included these higher-level taxonomic groupings in my analyses, fine-tuning my models to the species level would deliver more accurate results for each species. However, this issue should not limit conclusions from my study as I had a large sampling effort (Si et al., 2014) and I created a photo identification standard operating procedure with an implemented error checking strategy (Choo et al., 2020).

I selected my study sites based on careful consideration of the landscape in each of my study locations and worked with project partners in each study location to access sites which satisfied the requirements of my research objective. This opportunistic design introduced potential biases from 1) non-random camera arrays, and 2) placing cameras along game trails or in ways to try to maximize chances of detecting a mammal. Concerning the first potential bias, the detectability of a species is not the same in studies with random versus non-random camera trap designs (Hofmeester et al., 2017). This can be problematic when comparing multiple study results without considering camera trap placement designs. I attempt to bring awareness to this potential bias by explaining my study design in detail. Concerning the second bias, targeting certain features within a site, such as game trails, can generate higher detections of species (Kolowski & Forrester, 2017). This can introduce a bias if not applied to all sites or compared without standardization between different studies. Also related to my camera trap placement, the viewshed of my stream cameras did not exclusively capture the stream habitat type. In some cases, I detected mammals on my stream cameras which were using the edge of the riparian habitat. However, I assumed that should any individual be detected on the stream camera, it would be using the stream habitat type.

I did not holistically address imperfect detections (i.e., cases where a species was present but not detected), however I attempted to minimize detection biases by standardizing my camera deployment procedure in the field and excluded species with low detections, accounted for visibility differences, and compared detections within species rather than between species in my model. It is important to recognize that the species I found on my cameras and their probability of detection could have been at least partially impacted by my study design. As well, because I assumed perfect detections, there is some level of uncertainty around which mammals were only found in a particular habitat type. All of the species that were found in only one habitat type were also excluded from my model due to low detections and poor model convergence. While it is possible that some of these mammals are specialists to a particular habitat type, it is also likely that my sampling design or total effort excluded them. Since I did not include species with few detections in my model, further research is needed to examine how environmental characteristics impact less frequently detected species and those with low probabilities of detection (i.e., small and elusive species).

2.4.4. Management toward resilience at the habitat patch and landscape scales

As supported by the results of this study, managing landscapes is a balancing act of many environmental variables interacting simultaneously. Enhancing one resource or environmental condition will be favorable for some species and not for others. With high levels of disturbance, framing management towards resilience is vital to the health of a landscape and the ability for wildlife to persist in available habitat patches. Resilient landscapes can maintain major biotic functional groups after a disturbance (Holling, 1973; Holling 1996; Côté & Darling, 2010), especially those caused by climate change or development intensity. However, my results suggest that development intensity and other environmental characteristics (which may be altered by climate change) are shaping mammal communities at both habitat patch and landscape scales.

With resilience in mind, my results suggest that riparian areas are critical habitat to include in landscape management plans. I found that riparian areas in my study locations supported diverse mammal species. Given that I observed overlap among the three habitat types by the majority of species, riparian areas are likely most supportive as habitat for mammals when they are also connected to their neighboring stream and matrix habitat types. Since stream channel morphology did not play a large role in influencing habitat use by mammals, my results suggest that riparian areas surrounding streams of different sizes and morphologies are worthy of protection in an interconnected landscape, because wildlife have different preferences for topographic and morphological conditions. What was more influential to species and communities was proximity to development and elevation. Development intensity is decreasing available habitat and connectivity, reducing complexity within a habitat patch (Naiman et al., 1993), and reducing local functional redundancy (Devictor et al., 2007; Fahrig, 2003). Habitat complexity and functional redundancy are two essential components of resilient habitat patches. Climate change is causing unprecedented warming, shifting plant communities (Dwire et al., 2018) and altering the timing of snowmelt (Poff et al., 1996), consequently restructuring the environmental characteristics within habitat patches and along elevation gradients (Pucko et al., 2011). Scaling up to the landscape level, significant changes to local habitat patches alter available resources and environmental conditions across the landscape, so having less resilient habitat patches also reduces the capacity for entire landscapes to support diverse wildlife populations.

This research highlights the need to manage at both the landscape scale and the habitat patch scale. Watersheds are interconnected from their headwaters to their mainstems, and ecological processes occurring everywhere within the watershed are dependent on this bidirectional connectivity and movement of resources and organisms (Freeman et al., 2007). As human-caused development intensifies, maintaining intact landscapes will be increasingly difficult, yet vitally important to overall resilience. However, attention towards the finer habitat patch scale is necessary to meet the resource and environmental condition requirements of specific species present in a landscape. Healthy landscapes will have a variety of habitat patches for wildlife to select (Looy et al., 2013), and if major disturbances (like fires and floods) consume several habitat patches, connectivity throughout the greater landscape will allow populations to move to suitable habitat patches while part of the landscape is recovering.

Concluding remarks

The research conducted from the first chapter of my thesis demonstrated that riparian areas have the potential to serve as resilient residential habitat and as movement corridors for wildlife. From that chapter, I propose that landscape managers should incorporate riparian areas of a variety of widths and landscape features in their landscape resilience strategies. The research conducted from the second chapter of my thesis demonstrated that riparian areas are an important habitat type for many mammal species, though their ability to support mammals could be facilitated by connections to neighboring habitat types. The habitat use patterns by mammals in this study were different based on various environmental characteristics. Development intensity and climate change continue to shape the environmental conditions within a landscape and individual habitat patches, so landscape managers must anticipate the species that will benefit from these changes and the species that will not benefit. As anthropogenic development and climate change intensity, protecting riparian areas of many widths provides space and a variety of microhabitats to support diverse biotic functional groups. Landscape managers should also promote riparian connectivity throughout a landscape. That way should part of a landscape be disturbed, wildlife can move to intact habitat patches while the disturbed habitat patches recover.

Working on this thesis taught me a great deal about the challenges of applied ecological science. From the very beginning, when I was crafting this research question and design, it became clear that textbook scientific questions and designs are not always feasible once you arrive at a site. This research objective was carefully reshaped many times before settling on its current form. To me, this highlights the value in immersing oneself in a study location. I owe much of my knowledge about my study locations to spending time at each site and talking to partners who have lived in my study locations for many years. One benefit of applied ecological science is the opportunity to work with partners and engage with the public. I had the privilege to work closely with professionals who are making real change in their communities. Hearing their ecological concerns and objectives helped steer my research to make it more applicable for their work. I was also given the opportunity to connect my research with the public. Whether it was answering questions while out doing field work, leading an educational Nature Walk, or hosting more formal teaching sessions, it was enjoyable to see people reconnect to their natural surroundings.

This thesis has affirmed my suspicion that ecology is a complex science. There are many variables acting simultaneously on a system, which makes it difficult to understand the consequences of any one variable in isolation, like human-caused development or climate change. My hope is that shifting management towards resilience lessens the need to understand variables individually, but instead focuses on allowing the system to function as a whole and providing space and time to recover should disturbances occur.

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Appendix A.

A detailed description of sites selected for this study

Maple Ridge

Hooge

This site was within Harry Hooge Park, which is in a well-developed residential area with a public elementary school nearby. The stream itself is small and shallow. It has many arched branches that overhang the stream, making it a very dense and wooded area. There is not a lot of understory green vegetation, particularly in the riparian area, compared to some of the other sites. There are several paths leading from the main walkway through the riparian area down to the stream. It is clear that this is an active site for the schoolchildren to explore. I originally placed the cameras nearby the stream, on what I believed were animal tracks. Upon revisiting the site a week later, the cameras had been tampered with and caked in mud. The animal paths were actually human paths. I moved the camera to deter the children. The stream camera's new location was further away from the school, pointed downstream, and had a narrow field of view because of all the overhanging branches. The riparian camera was originally low to the ground on a fallen tree that pointed parallel to the stream. I moved it and also pointed it parallel to the stream, but on the other side of the stream and inside a thick patch of salmonberry. The matrix camera was originally close to but concealed from the main pathway. That camera was vandalized during the summer deployment period and was moved to a small, wooded patch off a walking path approximately 450-meters southeast of Harry Hooge Park.

Thornvale

This site was located in a sparsely developed residential area. This site sat at the edge of developed and currently undeveloped land, however, there were active construction projects occurring all around. Thornvale Creek is a small creek that joins with Kanaka Creek at a very productive intersection. The stream is a salmon spawning site, however, there is concern that this area could be an ecological trap as the shallow water and heavy extraction could be detrimental for the fish population reproduction. I placed the camera in the section of undeveloped land, however, there were walking paths frequented by humans and horses leading up to the site. Being as this was supposed to be a semi-residential site, I kept the cameras close to the walking paths. The trail eventually crosses the stream. Either side of the stream was very steep. I placed the stream camera further back from the streambed because there were no trees growing right along the stream itself. I sharply angled the camera downward to directly face the stream and tested to be sure it captures things in the stream. The riparian camera I placed to capture wildlife moving parallel to the stream on a flattened section of the riparian area. The matrix camera I placed higher away from the stream, very close to the walking path, although not pointing at the path. I had the camera pointing uphill and angled accordingly to capture mammals moving near the path.

Alder

This site was in a park within a residential area, but one that is less developed than Harry Hooge Park. There was a nearby playground and lots of walking and biking paths in this park. The cameras were located near a bridge that crosses the stream. This bridge is wide and strong enough to support vehicle traffic. There was a human path that leads from the bridge to a rocky beach. At first, the stream and riparian cameras were on the same tree just on the other side of that rocky beach. I revisited the site and decided that the cameras were at risk of theft and unnecessary human photographing, so I moved them to a more discrete location. At the new location, the stream camera pointed directly at the stream but was surrounded by brambles. The riparian camera was set back and was pointed upstream in an opening in the riparian area. I think wildlife are using that area because there were smaller paths weaving through that area and connecting over to the matrix camera. The matrix camera was originally pointing towards the stream but was set far back. After moving the riparian camera, I also changed the angle of the matrix camera to point parallel to the stream. I felt that this better captured the matrix habitat type and differentiated from the riparian camera. All cameras were surrounded by human trails, but to access the cameras required some hiking through the forest.

Codd

The Codd Wetland Ecological Conservancy Area was recently purchased by Metro Vancouver to be converted into a regional park. It used to be a place where humans would regularly come to practice shooting, and an agricultural operation was running, but it became evident that it was a productive wildlife passage site as there was scat and tracks everywhere. This site is partially grassland/pastureland and partially a wetland area with a poorly managed dyke. I decided to place all cameras on the farmland/grassland side because I defined this site as a developed or semi-developed agricultural site. The stream camera was low to the ground and pointed at an angle towards the stream. There was a faint animal path coming out of the water, but the other side of the stream was a dense patch of brambles. I believed it unlikely that anything, unless small, would be navigating through the other side of the stream. Instead, I thought it was more likely that animals were using the streambed to move or the grassland on the side of the stream the camera was on. The riparian camera was placed on the other side of the stream from the stream camera and pointed at a noticeable wildlife path. There was a plank that allows human passage across the stream, but beneath that plank was a beaten down wildlife path. I checked the camera a few weeks after deployment and noticed that something ran into the camera and knocked it out of place. I also noticed scat very close to the plank. The camera looked over the stream but is higher on the tree to capture both anything in the riparian area on the other side of the stream or anything walking across the plank. The matrix camera was fastened to a telephone pole and pointed into the grassland nearby. There was a mowed and driven path that would be easy movement for wildlife, which the camera could detect. This site had reported elk in the area, according to Dennis Hart from Metro Vancouver.

Kanaka

I was introduced to this site, Thornvale's site, and Codd Wetland by Roy Teo and Chris Kimmel from Metro Vancouver. There was ample evidence of wildlife use of the area, particularly defined wildlife paths. There were lots of upland development, which was visible from all sides of the creek. The team at Metro Vancouver believes that the development is pushing wildlife towards the riparian area and streambed. There was new development happening on the 110 Avenue side of the stream, with lots of signs and active construction already in motion. I chose the larger stream because of the variation I needed in stream size, but also because I sampled on the Thornvale headwaters further upstream. The stream camera was low to the ground, angled and pointed upstream. It was originally on a fallen log, however, during the fall, the camera was swept downstream a few meters during a flash flood, so I repositioned the camera approximately 5 meters back from the stream. I fastened it to a tree and pointed it down, so it overlooked the stream in approximately the same position. This camera was stolen during the winter data collection period. In March, I reinstalled a camera directly across the stream from the previous location but positioned about 7 feet off the ground in a tree overhanging the stream. I drilled the camera into the tree in hopes to deter thieves. The riparian camera was pointed in a corridor parallel to the stream. There were apparent wildlife paths and lots of vegetation cleared out. The matrix camera was on the opposite side of the stream as the other two cameras near where all the development was off 110 Avenue. It was still within the Metro Vancouver gated property, but there were lots of nearby walking paths for the locals who come down to the water to fish. There was an old wire fence that was broken next to where I placed the camera. There was a dried streambed nearby and an open clearing in front of the camera.

Highway

This site was located near Golden Ears Way, a busy highway that sees lots of traffic daily. There was a paved walking path that meanders along the stream. I classified this stream as large and deep, and it was surrounded by a grassy riparian area. On one side of the stream is the highway and on the other side is a residential area with a fence that blocks access to the neighborhood. The stream camera was placed on an angled tree that hung over the stream. The camera faced downstream. Originally, I had the camera very low because the embankment was steep next to the stream. I had to go back and move the camera up vertically because the grass was growing too tall into the frame of view. The camera had the same angle downstream but was pointed down to capture animals in the water. The riparian camera was hidden in a patch of trees and shrubs. It was tricky finding spots to place all cameras because so much of the area was exposed to human view and given that this area is frequently trodden by people, there was a fear of theft at this site. The riparian area was more wooded, but there was a clearing down to the stream where I believed wildlife were accessing the stream. The matrix camera was more difficult to access because it was in a thicket of salmonberry. It was separated from the stream by a walking path and positioned towards the fence line of the residential neighborhood. I chose this site because it was as close to the neighborhood as I could get while still being concealed from view from humans.

Park

This site resembled a much less developed version of the Highway site. There was a large and frequently trafficked walking path that divided an open grassy area. On the left of the walking path was a sparsely populated residential area and a field used for equestrian training, while the stream was on the right. There was active construction on Park Lane. The stream camera was accessed via a small opening in the shrubs. I believed wildlife used this path because the vegetation was not trampled enough to be used by humans. The camera pointed downstream on this medium-sized stream. The riparian camera was under a spruce tree that provided a small clearing in the vegetation. It was pointing towards the stream, although the stream was not visible from the camera's location. The matrix camera was in the riparian area but pointed towards the walking path. It was difficult to conceal this camera, but it was installed in a drainage area that was hidden from human view by an isolated patch of Japanese knotweed. I placed the camera high because I needed to look over some of the shrubs and stumps that I could not cut. I angled the camera downwards, so it captures the short visibility distance in the drainage area.

McKenny

This site was in a densely developed residential area. There were residential complexes on either side of this stream. A fence ran the length of the stream, preventing access beyond the riparian area into the residential neighborhood. This site had a steep slope down to the streambed, and human paths ran along the top of the slope, near the fence. People have thrown trash into the riparian area, which was distributed throughout the site. The stream camera was low to the ground and pointed at a few fallen logs, perpendicular to the stream, that could provide great passage for wildlife across the stream. The stream itself was small and swampy. The riparian camera was on the slope, pointed parallel to the stream on a path uncertain whether it was created by humans or wildlife. The matrix camera was higher on the slope, on a much steeper angle also pointed parallel to the stream. There was no apparent wildlife path in this area. This site was challenging because there was no real matrix habitat due to the residential development and fence, and placement on top of the berm was risky due to evident human paths.

Green

I had to hike along a walking path to access to this site. There was a steady descent down to the stream, and a steep drop in the last section of land next to the stream. I traversed the forest away from the trail to avoid human presence as this site is supposed to be an undeveloped site. The stream was large and fast flowing. I placed the stream camera on a tree high on the streambank looking over a rocky part of the streambed. The riparian area was on the steepest part of the land next to the stream and was on a tree that overlooked the area and appeared to contain a wildlife den. I pointed it towards a few believed wildlife trails that lead to the water. The matrix camera was higher in the forest, far from the other two cameras. It had an open forest flood that was covered in moss. It was angled down slightly to capture small mammals on the forest floor at this sloped site.

Marian

There were several access roads that encircle this part of the stream and there was a drivable bridge that crossed the stream. I placed the stream camera at a tree right on the streambank and pointed it directly across the stream. On the other side of the stream was a suspected wildlife trail. The riparian camera was set back and in an open part of the riparian area where wildlife would have easy access to the stream. This riparian area was much mossier than other riparian areas I surveyed in. The matrix camera was on the opposite side of the stream as the other two cameras, accessed by a smaller access road. I hiked down towards the stream, but it is still quite close to this quieter road. The camera pointed parallel to the stream. While wildlife might have been using the access road, if they were not and traveled in the matrix habitat type, I was likely to capture it on this camera.

Blaney

I hiked in quite a bit to this site. This area used to be an old logging site, and there was leftover machinery that the forest reclaimed. There was a meadow dominated by thorny shrubs at this site, but above the meadow was an old access road from the logging days. The road was flat and had an open forest floor. The matrix camera was on this access road and pointed parallel to the stream. The stream camera pointed high above the stream at a large log that crossed the stream. The camera detected movement on the log and near or in the stream. The riparian camera was the nearest flat section I could find, a few meters from the stream camera. It pointed parallel to the stream. The forest floor at this camera was open and it would be very easy for wildlife to move through this area.

Webster

This site was at the edge of developed land and natural habitat. I saw signage that this area will soon become a larger residential complex, and I even saw trees marked for removal. The municipally owned property was only a tiny parcel of land on either side of the stream, so if this area gets developed it could be quite problematic for the wildlife. I bushwhacked to get to the site, which was on the opposite side of the stream as the development complex. I placed the stream camera on a small island pointing downstream. This camera was false triggering despite clearing all the vegetation. I replaced the camera with a Bushnell model temporarily while I repaired the Reconyx camera. The riparian camera was almost next to the stream camera but was up much higher and pointed across a small fork in the stream onto the riparian area. The streambank was steep and sudden in this section, so the riparian area was set up higher than the streambed. The matrix camera was further into the woods, pointed parallel to the stream in an open patch of the forest where it would be easy passage for wildlife.

Squamish

FSR

This site was an active logging area and was accessed from a forest service road that was frequented by logging trucks. The site was located high on a mountain at a small headwaters stream. The cameras were installed very near the logging road. This site was supposed to be one of my undeveloped sites, but it was more utilized by humans than some of my other undeveloped sites. I had to keep the cameras close to the road because the embankment on either side of the road was so steep that the stream flows significantly less the higher uphill. The stream camera was pointed directly across the stream near a log that crossed the stream. The riparian camera was set further back pointed directly at the stream on the opposite side of the stream from the stream camera. The matrix camera was deeper into the woods, but still near the logging road and was pointed into a depression of the forest.

Lower Mashiter

This site was surrounded by industrial complexes. There was a bridge that crossed the stream and several hiking trails that lead to the water's edge, and it was clear that humans were using this site to swim downstream. I also noted a hunting hut near where the cameras were installed. The stream camera was across the stream from the other two cameras and was easily accessed from on the parking lot of an industrial complex. It was installed on a tree a few meters away from the streambank and angled downward toward the water. The riparian camera was in a clearing and pointed parallel to the stream along a wildlife path. The matrix camera was tucked away in a bundle of smaller trees and concealed by moss. There were some paths along a rock wall that wildlife might be using. The camera pointed at the rock wall and parallel to the stream. The matrix habitat patch was very small at this site because development encroached the stream.

Britannia

This was a very urban site. The stream was surrounded on the west side by a well-developed industrial complex and on the east by the Sea-to-Sky Highway. There was a walking path along the stream that was heavily trafficked. The stream itself was very small and murky. It appeared more as a drainage creek than a flowing stream. The stream camera was on the west side of the stream and was on the only tree that was close enough to the water to see wildlife in the stream. The camera directly pointed at the water. It was visible to cars that are stopped at the traffic light, so was at risk for theft. The riparian stream was on the east side of the stream and was in a bundle of trees that overlooked the grassy riparian area towards the stream. The matrix camera was in another bundle of trees on the east side that had no understory vegetation in it. The camera was pointing towards the highway but was concealed from view.

Upper Mashiter

This site was very difficult to access. There was development on both sides of the stream, but because the embankment was so steep down to the stream, there was quite a large riparian buffer compared to other sites. There was a bridge that overlooked the water in the valley and there was a trail that you can access to get down to the stream. This was clearly occupied by humans often as there was a skate park and a heavily used path to the water. This river was large and very fast-flowing. The stream camera was in a tree that was high above the water and was facing upstream. It was hidden from view and angled down severely towards the water. The riparian camera was pointed directly at the stream but was set back about 15 meters. It is also angled down as the embankment was steep there. The matrix camera was high on the embankment and was difficult to get to. The camera pointed parallel to the stream along a ledge on the hillside that could be useable to wildlife.

Ring

This site was more remote access. You get to it by driving along a forest service road until you get to a parking lot used frequently by mountain bikers and hikers. The surrounding area had many recreational trails and there was steady human traffic. There were smaller trails that branched from the main mountain bike trail that get us closer to this site. The stream was big but not very deep and had a rocky bed. This site was in an undeveloped area, remote enough to not have cellular service. The stream camera was low to the ground and pointed directly at the stream. There was a large log that crossed the stream that the camera faced. The riparian camera pointed towards the stream as well but was set about 15 meters back in a swampy area. The matrix camera was closer to the small mountain bike trail and pointed parallel to the stream in an open and flat forest floor.

Edith

This site was within Alice Lake Provincial Park. You access this site via a hiking trail that takes you up a fairly significant pitch. There was a bridge that crossed the stream and then the trail headed off deeper into the forest. I hiked off the trail to avoid being detected by humans and placed the stream camera higher on the streambank but pointed down to directly face the stream. I could not find any other trees that were closer to the water that were not easily detectable by humans. The stream was small, so even though the camera is a few meters away from the streambank, it still detected movement in the water. The riparian camera was on a tree adjacent to the stream but was pointed parallel to the water to capture anything coming down to the stream approximately 30 meters downstream from the stream camera. The matrix camera was far from the other two cameras. The riparian area was large at this site and the hiking trail picks up right when the forested habitat type begins. I hiked higher on the mountain to get to a flatter section and navigated off trail to conceal the camera. The forest at this site was very open.

Jack

This site was in Alice Lake Provincial Park. I accessed this site via a hiking and biking trail from Alice Lake. Compared to Edith, this site was much flatter, however, there was still a significant berm on the west side of the trail to get to the matrix habitat type. This stream was extremely small and was dry for a significant period of this study. The stream camera was pinched between the stream and the trail and was angled slightly downward. The riparian camera was set about 15 meters away from the stream and was very close to the trail. It was concealed by a log and was therefore lower to the ground. Its viewshed was towards the stream on a believed wildlife path. The matrix camera was on the west side of the path and above the berm in a flat and open habitat. It pointed parallel to the stream.

Hop

This site was located at the end of a residential neighborhood. Immediately after development stopped the stream ran perpendicular to the road. There was a bridge and on the east side of the access point are lots of trails that are used often by people. I placed cameras on the west side of the trails to protect them from human view. However, I noted a hammock near where I installed the cameras, so I expected human activity. The stream camera was between the stream and the residential area and was facing upstream. There were not many choices for the stream location because many trees were in plain view of humans passing by. The riparian camera was on the same tree as the stream camera but pointing towards the residential neighborhood. The matrix camera was pointed away from the stream in an open area in the forest.

Dryden

This site was in the middle of a residential area. It was classified as a medium-sized stream that was tucked between rows of suburban homes. There were fences and large bushes that separate people's backyard from the riparian area. There was also a short walking path that connected neighborhoods, which I used to access this site. The stream camera was pointed upstream slightly. The riparian camera was a few meters away from the stream camera and was pointing in a small clearing in the vegetation. The ground was covered with forbs, which would be relatively easy for wildlife to move through, although I did not notice wildlife trails. The riparian camera was very close to the walking path. The matrix camera was on the edge of the forested area and pointed into an open field very near the neighborhoods. There were some paths in this area, although uncertain whether they were human- or wildlife-generated. I chose this area because the matrix habitat type here was very small and I wanted to see if wildlife were choosing the more "natural" area, which was the riparian and stream area, or the more human disturbed, which was where the matrix camera is.

Stawamus

This site had a large stream found in a ravine in an undeveloped site with limited accessibility. There was a hydropower station near this site, but I hiked in to get away from the development. The embankment on the side of the river was steep. The stream camera was set high off the ground because this river filled up with a lot of water. It was angled down slightly to capture movement in the river, and I cleared lots of overhanging vegetation. The location looked like a small beach, which I believed would attract lots of wildlife to drink and swim. About 10 meters away, I installed the riparian camera on a tree that was growing out of a nurse log. There were potential dens underneath this tree, and it was very near the stream. I faced the camera directly away from the stream pointing across another log and into the riparian area. I wanted to see what was crossing the log. The matrix camera was very high on the embankment of a steep slope. It pointed downhill slightly at a flatter ledge that wildlife may be using to move through this area.

Mamquam

This site was on a large river at the bottom of a ravine, making it my steepest site to access. At the top of the ravine was a forest service road, which people use to hike and bike. There was also evidence of human activity in an around the cameras, including campfire remains at the top of the ravine, and walking paths down to the water's edge. I placed the stream camera high on the streambed and pointed it down severely towards the water to capture movement in the water and on the streambed. This river was very large and fast-flowing, so I believed that if mammals were using the stream for movement, they would walk on the streambed, but not in the water. The streambed was very rocky and wide. The riparian camera approximately 30 meters away from the stream camera, pointed at an opening in a log with apparent wildlife activity. It was angled upwards and away from the stream. The matrix camera was pointed parallel to the stream and was up high, almost to the top of the ravine. The camera was still on a steep slope but was very close to the walking trail. After noticing evidence of human use in the area, I moved the camera 10 meters northwest and reoriented 180 degrees to better conceal it.

Plateau

This site was in a residential area at a medium-sized stream. This was active cougar habitat, according to Meg Toom, a former conservation officer in the Squamish area. There were houses and roads on all sides of this parcel of land, but the stream was enclosed by a buffer of forested habitat type. There was a walking path high above the stream on the hillside nearby. The stream camera was installed on the south side of the stream, pointing upstream, and was low to the ground. The riparian camera was installed on a dead tree on the north side of the stream and was pointing parallel to the stream, very close to the water's edge. The matrix camera was above a small berm on the north side of the stream and was in a flatter section of forest. It pointed parallel to the stream along a believed wildlife path. It was pinched between the stream and walking path above.

Appendix B.

Camera deployment procedures and covariate collection

Additional information about the camera installation process

Before fastening the camera to the tree, I turned the camera on and verified that the preprogrammed date and time were correct (Table B.1). I recorded the camera's location on a GPS unit, and I modified the coordinates in the camera to match that of the current site's location.

Table B.1. The settings applied to each Reconyx camera trap before installation in the field.

Motion		Default or Customized (rationale)
Date	Set at site	Customized (create timestamp)
Time	Set at site	Customized (create timestamp)
Location	Other	Customized (default is USA)
Set Location	Set unique coordinates at site	Customized (geolocate detection data)
Geotag	Yes	Customized (geolocate detection data)
Sunrise	6:09	Customized (specific to study locations)
Temperature	Celsius	Customized (convert to metric)
Battery Type	NiMH	Customized (specific batteries purchased for my camera traps)
Motion	On	Default
# Pictures	3	Customized (capture animal activity)
Time Between Pictures	Rapid Fire	Customized (capture animal activity)
Quiet Period	15 seconds	Customized (reduce instances of continuous detection of the same individual)
Sensitivity	High	Customized (capture both large and small mammals)
Motion Schedules	24hr	Customized (no confusion with AM/PM)

Time Lapse		
Lapse Pictures	On	Customized (capture photo of site twice daily)
# Pictures	1	Customized
Lapse Video	Off	Default
Interval	12hr	Customized (to capture at noon and midnight)
Lapse Schedule	24hr	Customized (one photo at noon, one photo at midnight)
Day/Night		
Take Pictures	Day/Night	Default
Take Video	Day/Night	Default
Flash Output	High	Default
Shutter	1/120th	Customized (faster shutter speed)
Max ISO	1600	Customized (increase sensitivity)
User Label	C1-C72	Customized (unique name for each camera)
Codeloc	Did not use this feature	Default
Date/Time	Confirm correct at site	Customized (create timestamp)
Location	Confirm correct at site	Customized (geolocate photo data)
Resolution	Standard	Customized (full resolution photo)
Other	Did not use this feature	Default

Once all settings were adjusted, I activated the "WalkTest" mode on the camera and secured it to the tree. The "WalkTest" mode allowed me to see the camera's full range of detection. It blinked red each time it sensed motion in the frame without capturing and storing image data. Once I understood the viewshed, I cleared vegetation in front of the camera to avoid triggering false detections. To prevent theft, I encased the cameras in a lockbox and passed a cable lock through the lockbox and around the tree. I also tied an identification label that provided my purpose of research and contact information (Figure B.1).

This camera is being used for scientific research on wildlife. Please do not tamper with the equipment or the surrounding habitat. Any images of humans will be made unidentifiable, and we are not collecting information about you in any way. If you have any questions or concerns, please contact Kate Andy (MRM graduate student) or Dr. Chelsea Little of the Little Ecology Group. Thank you!

Figure B.1. The identification label that was attached to each camera.

To deactivate the "WalkTest" mode and activate the data collection setting of the camera, I let the camera sit idly for 2 minutes. In that time, I measured the camera's orientation, quantified the camera's range of visibility, and recorded any other notes about the site. To determine the camera's orientation, I placed a compass on top of the camera and measured the direction in which the lens was pointing. Visibility was observationally quantified by estimating the distance the observer could see when at the camera's level before the view was obstructed. I defined obstruction as a blockage in the direct viewshed caused either by a large change in the slope, dense vegetation, or rock walls.

Pilot study description

Before deploying camera traps in the field, I practiced setting up the cameras at Simon Fraser University's campus in Burnaby, British Columbia, Canada. My objective was to 1) understand the camera's viewshed and 2) determine whether my stream camera should be angled slightly upstream/downstream or pointed perpendicular to the stream. I set up two Reconyx Hyperfire 2 cameras with identical settings (Table B.1) on the same tree alongside a stream. One camera was facing upstream, and one camera was perpendicular to the stream. I left the cameras out for three weeks and then compared species richness and the number of detections per species. My results suggested that the camera angles produced similar results.

Bushnell camera trap settings

Table B.2. The settings applied to each Bushnell camera trap before installation in the field.

Date/Time	Set and confirm in field
Mode	Camera
Image Size	8M Pixel
Capture Number	3 Photos
Interval	15sec
Format	Execute
NV Shutter	Long Range
Camera Name	Cam64
Time Stamp	On
Field Scan	Off
Coordinate	On (set in field)
Sensor Level	Auto
Camera Mode	24 Hours
Default Set	Cancel
Version	BS938_1903270A

Supplementary information about covariates considered in my analysis

Table B.3. A complete list of environmental covariates collected for this project.

Variables were grouped by site location and habitat type and reported as a mean and range. For some seasonal variables, I included an average across season, but the range represents the total spread from all seasons. Variables with an asterisk next to it have a reported mode. The channel morphology variables were taken from the stream habitat type, so are only reported in the stream columns for each study location (and the other habitat types were replaced with "NA").

Variable	Maple Ridge Matrix	Maple Ridge Riparian	Maple Ridge Stream	Squamish Matrix	Squamish Riparian	Squamish Stream
Streambank height summer (meters)	NA	NA	1.36 (0.25 - 2.51)	NA	NA	2.09 (0.21 - 6.31)
Streambank height winter (meters)	NA	NA	0.75 (0 - 1.81)	NA	NA	1.40 (0.31 - 3.51)
Streambank height spring (meters)	NA	NA	1.00 (0 - 1.61)	NA	NA	1.22 (0.21 - 2.11)
Visibility distance fall (meters)	10.45 (0 - 25)	8.23 (4.5 - 15.3)	11.97 (0 - 36)	10.62 (0.21 - 2.11)	7.73 (4.5 - 11.5)	12.68 (4.4 - 29)
Visibility distance winter (meters)	10.82 (0 - 22.3)	9.28 (4.5 - 25)	9.40 (0 - 20)	9.82 (4.8 - 15.8)	9.44 (3.6 - 23.4)	13.63 (4.6 - 28.8)
Visibility distance spring/summer (meters)	11.89 (0 - 24.2)	8.36 (4.7 - 19)	7.95 (0 - 17.8)	10.16 (4.2 - 15.4)	10.13 (4.5 - 20)	13.33 (4.6 - 29.6)
Average maximum visibility distance	11.06 (0 - 24.2)	8.62 (4.5 - 25)	9.77 (0 - 36)	10.20 (4.2 - 15.8)	9.10 (3.6 - 23.4)	13.22 (4.4 - 29.6)
Wetted width summer (meters)	NA	NA	6.96 (1.78 - 15.4)	NA	NA	9.81 (0 - 23)

Wetted width winter (meters)	NA	NA	6.67 (0 - 18.1)	NA	NA	8.83 (2.6 - 16.4)
Wetted width spring (meters)	NA	NA	5.86 (0 - 16.2)	NA	NA	9.56 (0 - 24.1)
Average wetted width (meters)	NA	NA	6.68 (0 - 18.1)	NA	NA	9.40 (0 - 24.1)
Bankfull width summer (meters)	NA	NA	9.09 (2.95 - 19.6)	NA	NA	12.68 (3.9 - 28.3)
Bankfull width winter (meters)	NA	NA	9.01 (0 - 19.7)	NA	NA	13.34 (4.2 - 31.9)
Bankfull width spring (meters)	NA	NA	8.25 (0 - 19.6)	NA	NA	13.12 (3.1 - 30.5)
Average bankfull width (meters)	NA	NA	9.01 (0 - 19.7)	NA	NA	13.05 (3.1 31.9)
Average water depth summer (meters)	NA	NA	0.29 (0.12 - 0.587)	NA	NA	0.27 (0 - 0.633)
Average Water Depth Winter (meters)	NA	NA	0.22 (0 - 0.5)	NA	NA	0.20 (0.08 - 0.36)
Average water depth spring (meters)	NA	NA	0.23 (0 - 0.71)	NA	NA	0.28 (0 - 0.71)
Average water velocity summer (meters/second)	NA	NA	0.24 (0 - 0.73)	NA	NA	0.37 (0 - 0.73)
Average water velocity winter (meters/second)	NA	NA	0.33 (0 - 1.1)	NA	NA	0.33 (0 - 0.7)

Average water velocity spring (meters/second)	NA	NA	0.23 (0 - 0.93)	NA	NA	0.44 (0 - 1.07)
Total DBH	32.87 (0 - 60.21)	25.63 (10.93 - 60.81)	20.07 (2.75 - 34.32)	(22.38 - 62.91)	34.31 (10.95 - 60.71)	30.86 (9.49 - 46.88)
*Stream order **	NA	NA	2	NA	NA	1, 4
Canopy cover summer	75.52 (31.2 - 367.9)	53.45 (30.94 - 99.84)	69.82 (37.18 - 239.2)	52.22 (35.88 - 71.24)	52.67 (24.7 - 150.54)	58.13 (34.32 - 94.9)
Canopy cover fall	101.76 (0 - 380.64)	90.99 (53.82 - 176.54)	100.92 (0 - 225.42)	67.86 (34.84 - 140.92)	63.44 (33.02 - 114.4)	79.76 (42.38 - 192.4)
Canopy cover winter	127.02 (0 - 351.26)	118.47 (67.6 - 236.6)	126.06 (0 - 275.34)	90.76 (50.7 - 191.36)	97.72 (41.08 - 249.6)	115.92 (39.78 - 217.1)
Canopy cover spring	100.38 (0 - 391.3)	67.95 (43.94 - 117.78)	85.84 (0 - 212.94)	67.99 (46.8 - 98.02)	68.25 (40.04 - 157.82)	77.70 (53.3 - 125.32)
Average canopy cover	104.88 (0 - 391.3)	82.72 (20.94 - 236.6)	98.3 (0 - 275.34)	69.71 (34.84 - 191.36)	70.52 (24.7 - 249.6)	82.88 (34.32 - 217.1)
Woody height summer (meters)	0.02 (0 - 0.11)	0.06 (0 - 0.38)	0.06 (0 - 0.68)	0.08 (0 - 0.44)	0.09 (0 - 0.45)	0.10 (0 - 0.4)
Woody height fall (meters)	0.14 (0 - 1.22)	0.21 (0 - 0.69)	0.14 (0 - 0.70)	0.06 (0 - 0.32)	0.05 (0 - 0.37)	0.19 (0 - 1.19)
Woody height winter (meters)	0.11 (0 - 0.36)	0.11 (0 - 0.52)	0.17 (0 - 1.04)	0.03 (0 - 0.27)	0.04 (0 - 0.22)	0.02 (0 - 0.06)
Woody height spring (meters)	0.19 (0 - 0.79)	0.50 (0.02 - 0.94)	0.29 (0 - 0.93)	0.09 (0 - 0.67)	0.08 (0 - 0.47)	0.15 (0 - 0.77)
Herbaceous height summer (meters)	0.42 (0.03 - 0.97)	0.51 (0.04 - 1.11)	0.52 (0.06 - 1.62)	0.18 (0 - 0.47)	0.23 (0.01 - 0.70)	0.14 (0.01 - 0.43)
Herbaceous height fall (meters)	0.15 (0 - 0.79)	0.07 (0.01 - 0.19)	0.17 (0 - 0.45)	0.14 (0 - 0.44)	0.08 (0.01 - 0.30)	0.03 (0 - 0.13)

Herbaceous height winter (meters)	0.06 (0 - 0.21)	0.023 (4.00E-04 - 0.07)	0.04 (0 - 0.16)	0.021 (0 - 0.08)	0.01 (0 - 0.07)	0.01 (0 - 0.03)
Herbaceous height spring (meters)	0.09 (0 - 0.19)	0.061 (4.00E-04 - 0.12)	0.15 (0 - 0.62)	0.13 (0 - 0.4)	0.12 (0 - 0.31)	0.12 (8.00E-04 - 0.45)
Duff depth summer (centimeters)	2.47 (0 - 6.63)	2.08 (0.5 - 5.5)	1.63 (0 - 3.5)	4.06 (0 - 8.75)	2.44 (0 - 7.25)	2.08 (0 - 7.5)
Duff depth fall (centimeters)	2.17 (0 - 6.5)	2. (0 - 5.75)	2.85 (0 - 9.50)	2.99 (0 - 7.75)	3.25 (0.75 - 8.75)	2.13 (0 - 10)
Duff depth winter (centimeters)	2.06 (0 - 7.25)	1.86 (0 - 5.75)	1.98 (0 - 7.5)	2.13 (0 - 7)	1.13 (0 - 3.75)	1.54 (0 - 6.5)
Duff depth spring (centimeters)	1.60 (0 - 7)	1.92 (0 - 4.5)	1.65 (0 - 7.5)	3.23 (0 - 7.25)	2.17 (0 - 7.25)	1.88 (0 - 6.5)
Biomass principal component 1	0.36 (-1.61 - 8.16)	-0.01 (-1.92 - 1.22)	0.03 (-1.32 - 0.92)	-0.82 (-3.86 - 2.03)	0.23 (-2.07 - 2.90)	0.19 (-1.5 - 2.83)
Biomass principal component 2	-0.70 (-6.88 - 2.1)	0.18 (-1.23 - 1.07)	0.38 (-1.22 - 1.03)	-0.4 (-3.13 - 1.86)	0.2 (-1.52 - 1.92)	0.37 (-1.26 - 1.89)
Terrestrial principal coordinate 1	-0.02 (-0.14 - 0.21)	-0.01 (-1.92 - 1.22)	0 (-0.08 - 0.1)	0.01 (-0.09 - 0.07)	0.01 (-0.12 - 0.09)	0.01 (-0.12 - 0.08)
Terrestrial principal coordinate 2	-0.02 (-0.14 - 0.21)	-0.01 (-0.11 - 0.16)	-0.01 (-0.11 - 0.19)	0.02 (-0.04 - 0.14)	0.03 (-0.08 - 0.16)	0 (-0.14 - 0.11)
Stream quadrat principal component 1	0	0	-0.09 (-4.36 - 2.08)	0	0	0.01 (-3.23 - 1.62)
Stream quadrat principal component 2	0	0	-0.03 (-2.28 - 3.05)	0	0	0.03 (-1.98 - 2.3)

Terrestrial quadrat principal component 1	0.62 (-2.34 - 2.55)	0.03 (-1.93 - 1)	0.62 (-2.75 - 2.47)	-0.33 (-1.57 - 2.28)	-0.46 (-4.73 - 3.39)	-0.60 (-3.57 - 2.8)
Terrestrial quadrat principal component 2	-0.30 (-2.13 - 1.26)	-0.05 (-3.63 - 3.18)	-0.24 (-2.73 - 1.86)	-0.50 (-1.73 - 0.39)	0.13 (-2.05 - 2.75)	1.01 (-1.19 - 5.17)
Local aboveground biomass (megagram/hectare)	91.31 (22.06 - 173.85)	83.04 (12.88 - 173.84)	81.56 (3.71 - 173.85)	70.77 (1.54 - 144.72)	73.35 (1.54 - 144.72)	73.25 (1.63 - 144.72)
Small home range aboveground biomass (megagram/hectare)	70.61 (23.39 - 127.92)	73.08 (23.45 - 128.38)	70.95 (3.71 - 173.85)	89.072 (48.17 - 129.41)	89.23 (47.96 - 129.62)	89.33 (49.26 - 129.55)
Large home range aboveground biomass (megagram/hectare)	69.66 (34.43 - 102.23)	70.13 (34.71 - 102.28)	69.68 (34.70 - 102.26)	95.87 (91.83 - 98.99)	95.89 (91.82 - 98.95)	95.88 (91.82 - 98.97)
Local belowground biomass (megagram/hectare)	24.02 (8.62 - 39.38)	22 (4.53 - 39.38)	22.07 (4.53 - 39.38)	20.48 (2.96 - 34.90)	21 (2.96 - 34.9)	21.24 (5.19 - 34.90)
Small home range belowground biomass (megagram/hectare)	19.47 (9.62 - 30.64)	19.91 (9.92 - 30.71)	19.55 (9.66 - 30.72)	23.88 (15.91 - 31.34)	23.90 (15.87 - 31.38)	23.93 (16.13 - 31.27)
Large home range belowground biomass (megagram/hectare)	18.65 (9.62 - 30.64)	18.74 (11.04 - 25.88)	18.65 (11.04 - 25.88)	25.47 (24.61 - 26.21)	25.47 (24.61 - 26.2)	25.47 (24.61 - 26.2)

Local global human modification index	0.58 (0.28 - 0.89)	0.57 (0.28 - 0.89)	0.58 (0.28 - 0.89)	0.4 (0.23 - 0.61)	0.4 (0.23 - 0.61)	0.4 (0.23 - 0.61)
Small home range global human modification index	0.59 (0.28 - 0.85)	0.58 (0.28 - 0.85)	0.59 (0.28 - 0.85)	0.38 (0.17 - 0.54)	0.38 (0.17 - 0.23)	0.38 (0.17 - 0.54)
Large home range global human modification index	0.52 (0.32 - 0.69)	0.53 (0.32 - 0.69)	0.53 (0.32 - 0.69)	0.21 (0.17 - 0.23)	0.21 (0.17 - 0.23)	0.21 (0.17 - 0.23)
Local nighttime lights (nanoWatts/sr/cm2)	7.19 (0.62 - 23.84)	6.55 (0.62 - 23.84)	7.24 (0.62 - 23.84)	4.61 (0.49 - 31.89)	4.63 (0.52 - 31.89)	4.68 (0.51 - 31.89)
Small home range nighttime lights (nanoWatts/sr/cm2)	8.03 (0.611 - 26.58)	7.48 (0.62 - 27.86)	8.1 (0.62 - 27.54)	2.48 (0.58 - 10.32)	2.49 (0.58 - 10.32)	2.49 (0.58 - 10.35)
Large home range nighttime lights (nanoWatts/sr/cm2)	5.8 (1.1 - 12.93)	5.72 (1.11 - 12.85)	5.79 (1.1 - 12.85)	1.39 (1.14 - 1.47)	1.39 (1.12 - 1.47)	1.39 (1.13 - 1.47)
*Local land cover **	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest
*Small home range land cover **	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest
*Large home range land cover **	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest	Closed evergreen forest
Elevation (meters)	82.69 (5 - 316)	82 (3 - 312)	78.38 (4 - 311)	138.33 (13 - 445)	132.58 (13 - 442)	132.08 (13 - 438)

Distance from road (meters)	42.2 (3.21 - 101.75)	60.09 (12.02 - 143.21)	59.25 (8.03 - 169.6)	41.66 (14.48 - 70.25)	41.54 (13.17 - 79.36)	42.42 (4.56 - 79.79)
Maximum NDVI summer	8054.23 (6143 - 9218)	8204.25 (6464 - 9169)	8079 (6464 - 9169)	7963.5 (3920 - 9750)	8140.42 (3920 - 9820)	8134.58 (3920 - 9792)
Maximum NDVI fall	7555.85 (5654 - 9097)	7767.17 (5654 - 9347)	7604.62 (5654 - 9347)	7776.25 (4287 - 9651)	7833.67 (4287 - 9651)	7881 (4287 - 9651)
Maximum NDVI winter	7111.46 (4086 - 9458)	7338.67 (5133 - 9723)	7173.46 (5133 - 9723)	7329 (3231 - 9740)	7405.08 (3231 - 9214)	7492.17 (3231 - 9790)
Maximum NDVI spring	7656.31 (5926 - 9047)	7856.83 (5926 - 9047)	7708.31 (5926 - 9047)	7751.42 (5224 - 9740)	7774.08 (5224 - 9491)	7794.83 (5224 - 9740)
Average Maximum NDVI	7594.46 (4086 - 9458)	7791.73 (5133 - 9723)	7641.35 (5133 - 9723)	7705.04 (3920 - 9790)	7788.31 (3231 - 9820)	7825.65 (3231 - 9792)

Table B.4. **Complete list of species traits covariates collected for this project. Variables were reported as a mean with a range.**

Variable	Mean (Range)
Home range (kilometers)	32.79 (0 - 363.05)
Log-transformed body mass (grams)	7.94 (4.78 - 12.32)
Invertebrate diet (percent)	5 (0 - 40)
Mammal/bird diet (percent)	3.62 (0 - 100)
Reptiles/snakes/amphibians/salamanders diet (percent)	2.69 (0 - 20)
Fish diet (percent)	6.15 (0 - 90)
Vertebrates diet (percent)	2.69 (0 – 20)
Scavenge diet (percent)	1.92 (0 - 30)
Fruit diet (percent)	1.08 (0 - 50)
Nectar diet (percent)	1.53 (0 - 10)
Seed diet (percent)	6.5 (0 - 50)
Other plant material diet (percent)	14.75 (0 - 100)

A detailed description of how I collected each covariate

Environmental covariates

Observed Salmon Presence (Yes or No)

This column contains instances where I observed salmon in the streams while I was out in the field.

Salmon Presence (Yes or No)

This column includes instances where salmon were observed in the field, salmon habitat signs were noted, and additional research on salmon presence was performed. The following table describes the rationale and provides sources for the sites at which salmon were not observed in the field:

Site Name	Rationale
Blaney	Part of the North Alouette, which is salmon-bearing (*Salmon Spotting Map*, 2023).
Britannia	Drainage ditch.
Codd	Tributary of Codd Wetland, which is salmon-bearing (Office of the Premier, Ministry of Water, Land and Air Protection, 2004).
Edith	Neither Edith Lake nor Alice Lake contain salmon.
FSR	Extremely narrow and steep first order stream.
Green	Part of the North Alouette, which is salmon-bearing (*Salmon Spotting Map*, 2023).
Highway	Drainage ditch.
Hooge	Tributary of the Alouette River, which is salmon-bearing.
Jack	A far northern reach of Hop Ranch Creek and neither Edith Lake nor Alice Lake contain salmon.
Lower Mashiter	Reported salmon presence (Wada & Sander, 2005).
Mamquam	Reported salmon presence (Wada & Sander, 2005).
Marian	Part of the North Alouette (*Salmon Spotting Map*, 2023).
McKenny	Reported salmon presence (Corbett, 2013; Melnychuk, 2011).
Ring	Reported salmon presence (Wada & Sander, 2005).
Stawamus	Reported salmon presence (Wada & Sander, 2005).
Thornvale	Tributary of Kanaka Creek.
Upper Mashiter	Reported salmon presence (Wada & Sander, 2005).
Webster	Tributary of Kanaka Creek, which is salmon-bearing.

Streambank Height (meters)

The vertical distance in meters from the base of the water to the top of the streambank. I measured streambank height in the field using a Laser Rangefinder. There are three columns for this covariate, which are associated with the streambank height taken from the summer, winter, and spring field seasons.

Habitat Type (Stream, Riparian, Matrix)

A categorical variable indicating the type of habitat the camera has been surveying in. The stream cameras were on the streambank pointing in the water. The riparian camera surveyed somewhere within the riparian zone next to a stream. The matrix was any terrestrial landscape that did not include the stream or riparian area.

Visibility Distance (Line of Sight - meters)

This variable is described in three columns, which represent the fall, winter, and spring/summer seasons in which these measurements were taken. These data came from field measurements using a Laser Rangefinder to measure the furthest point the camera could see in its direct viewshed (not necessarily detection range). There is a fourth column which is the average maximum visibility distances across all seasons.

Wetted Width (meters)

This field-measured variable is the width of the stream where there is still water in it. The wetted width was collected three different times within the data collection period, corresponding to the summer, winter, and spring seasons. There is also a reported average across all seasons.

Bankfull Width (meters)

This field-measured variable is the width of the maximum potential for the stream to hold water. The bankfull width was collected three different times within the data collection period, corresponding to the summer, winter, and spring seasons. There is also a reported average across all seasons.

Average Water Depth (meters)

This field measurement is the vertical depth of the stream at the time of data collection. Seasonal depth is an average of three depth measurements, which represented the depth variation of the stream. I collected the average water depth for the summer, winter, and spring seasons.

Average Velocity (meters/second)

This field measurement is the velocity of the stream at the time of data collection. Velocity was collected using a flow meter. Seasonal velocity is an average of three velocity measurements, which were representative of the flow variation of the stream. I collected the average water depth for the summer, winter, and spring seasons.

Stream Order

This variable is the Strahler number for the stream where the camera bundle is located. I retrieved this data from iMapBC (Government of British Columbia, 2023).

Stream Morphology

This is a categorical variable of the classification of the stream morphology. The possible categories were cascade, pool-riffle, step-pool, plane-bed, and dune ripple. Morphology was assessed in the field.

Development Type

This is a categorical variable describing the type of development surrounding the camera trap. The categories were as follows: urban, residential, agricultural, and undeveloped. This data was retrieved from iMapBC (Government of British Columbia, 2023).

Total DBH

This variable is a sum of the diameter at breast height (DBH) measurements collected in the field during the summer tree inventory. This is a sum of the DBH of all tree measurements.

Dominant Tree Species

These three columns are the top three most frequently identified tree species counted within the 15-meter buffer around the camera during the summer field visit. This is a categorical variable. This variable excluded small trees that are sometimes classified as shrubs, including vine maple, common hawthorn, pacific crab apple, choke cherry, bitter cherry, and red-osier dogwood. If there was a tie in the frequency of trees measured within the buffer, the tree with the larger total DBH was used.

Canopy Cover

In the field, four canopy cover measurement were performed, which were used to calculate the total canopy cover for a given seasonal visit. The measurements are expressed as a proportion of tree-occupied canopy to open sky. Canopy cover was estimated for summer, fall, winter, and spring seasons, and I also reported the average canopy cover across all seasons.

Woody Vegetation Height (meters)

This variable describes the average of the tallest woody vegetation measured from quadrat surveys performed in the field. There are four associated columns representing each seasonal field visit. Each seasonal measurement is the average of six height data.

Herbaceous Vegetation Height (meters)

This variable describes the average of the tallest herbaceous vegetation measured from quadrat surveys performed in the field. There are four associated columns representing each seasonal field visit. Each seasonal measurement is the average of six height data.

Duff Depth (centimeters)

This variable describes the vertical depth of the duff, defined as the organic and decomposed substrate below the leaf litter. Duff depth was measured at each quadrat, for a total of four times per seasonal field visit and averaged. There are four columns associated with this variable, reflecting the duff depth of the summer, fall, and winter, and spring seasons.

Road Distance (meters)

This variable is the most direct linear distance in meters to the nearest major roadway. These data were collected from RStudio using the “osmdata” package (Padgham et al., 2017).

Normalized Difference Vegetation Index (NDVI)

This variable is the seasonal maximum output of the NDVI test per camera trap location. There are four columns associated with this variable, which correspond to the summer, fall, winter, and spring seasons. I included a fifth column, which is an average of the seasonal maximum NDVI values. NDVI measurements were generated in RStudio using the “MODISTools” package (Hufkens, 2022).

Elevation (meters)

The local elevation of each camera trap station was collected in RStudio using the “elevatr” package (Hollister, 2021).

Principal Component Analyses (PCA) and Principal Coordinate Analysis (PCoA)

I ran principal component analyses to ordinate the vegetation and quadrat data and a principal coordinate analysis to ordinate the shrub data collected in the field in order to reduce complexity of the datasets to two major components that explained the majority of the variation in the data. I scaled and centered all PCA and PCoA data to standardize the measurements for comparison.

- *Tree Biomass Principal Component Analysis (PCA)*

This variable interprets the output of a PCA from tree basal area data collected during the summer field visit. Two columns are associated with this variable and represent the first two principal components.

- *Stream Quadrat Principal Component Analysis (PCA)*

This variable interprets the output of a PCA from stream quadrat data collected during the summer field visit. Two columns are associated with this variable and represent the first two principal components.

- *Terrestrial Quadrat PCA*

This variable interprets the output of a PCA from terrestrial quadrat data collected during the summer field visit. Two columns are associated with this variable and represent the first two principal components.

- *Shrub Principal Coordinate Analysis (PCoA)*

This variable interprets the output of a PCoA from shrub presence/absence data collected during the summer field visit. I used a PCoA because the dataset contained Boolean matrix data. Two columns are associated with this variable and represent the first and second principal coordinates.

Google Earth Engine Data

I used Google Earth Engine Datasets to extract additional environmental covariates used in my analysis. For each dataset, I collected data at three different spatial scales: local to the camera trap (5-meter radius), a small home range (1449-meter radius), and a large home range (8623-meter radius). Home ranges were determined from the species traits dataset. I grouped taxa by home range and calculated average large and small home ranges.

- *Biomass (Mg/ha)*

I collected aboveground and belowground biomass indices for each camera trap station. The dataset is from 2010 and has a 300-meter spatial resolution. These data were gathered from the Global Aboveground and Belowground Biomass Carbon Density Maps dataset (Spawn et al., 2020).

- *Land Cover*

This variable contains discrete land cover classification data from a 2019 dataset for each camera. The data are visualized at a 100-meter spatial resolution. The data were gathered from the Copernicus Global Land Cover Layers: CGLS-LC100 Collection 3 dataset (Buchhorn et al., 2020).

- *Global Human Modification Index*

This variable indicates the Global human modification index from 2016 for each camera. The data are at a one square-kilometer spatial resolution. These data were gathered from the CSP gHM: Global Human Modification dataset (Kennedy et al., 2019).

- *Nighttime Light (nanoWatts/sr/cm^2)*

This variable is the maximum Day Night Band (DNB) radiance values from an annual global Visible Infrared Imaging Radiometer Suite (VIIRS) nighttime lights dataset. This dataset was produced from monthly cloud-free average radiance grids from 2020 to 2021. The spatial resolution is 463.83 meters. These data were gathered from the VIIS Nighttime Day/Night Annual Bank Composites dataset (Elvidge et al., 2021).

Species traits covariates

Home Range (kilometers)

The average home range per species. Data on home range were obtained from Broekman et al. (2022).

Body Mass (grams)

This variable is the body mass of the average individual of the corresponding species. The data come from the EltonTraits 1.0 dataset (Wilman et al., 2014).

Diet

Values in these columns represent a percent use of the following food sources:

- Invertebrates
- Mammals/birds
- Reptiles/snakes/amphibians/salamanders
- Fish
- Vertebrates
- Scavenge
- Fruit
- Seeds
- Other plant material

The data come from the EltonTraits 1.0 database (Wilman et al., 2014). Some taxa were missing data from the EltonTraits 1.0 database, so diet data for these taxa came from the Animal Diversity Web database (University of Michigan, 2020). The table below explains how the missing information was supplemented.

Taxonomic Group	Data Source
Domestic dog	Coyote data from EltonTraits 1.0 as proxy
Elk	Mule deer data from Elton Traits 1.0 as proxy
Martens	Cougar data from Elton Traits 1.0 as proxy with modifications from Animal Diversity Web
Domestic cat	Animal Diversity Web
Chipmunks	Gray squirrel data from Elton Traits 1.0 as proxy with modifications from Animal Diversity Web
Snowshoe hare	Animal Diversity Web
Rats and mice	Gray squirrel data from Elton Traits 1.0 as proxy with modifications from Animal Diversity Web

Appendix C.

Wildlife insights photo identification protocol

The Little Ecology Group

Thank you for your help processing our photo data! There are a lot of photos to get through, so we really appreciate your help.

Background on the project:

British Columbia is composed of a linked network of diverse landscapes, spanning from kelp-dominated oceanic ecosystems to jagged mountain ranges, all of which creates tremendous opportunity for wildlife to flourish. However, human-driven development has directly threatened the biodiversity in this province by severing connectivity between ecosystems and restricting movement of wildlife within suitable habitats. Access to suitable habitat is a growing concern for wildlife as climate change is altering landscapes faster than wildlife can adapt to. One way to mitigate these negative impacts is to conserve habitat corridors that join larger protected areas. Streams and riparian areas, which are subject to some environmental protections in many areas, are often left partially intact even when they are impacted by development. Riparian areas share characteristics of many different habitat types, and their high levels of resources and structural complexity support not only a variety of organisms but surrounding habitat types as well. Thus, riparian corridors could enhance resilience against the pressures of urbanization and climate change by connecting larger reserves or being suitable habitat for wildlife. The objective of this project is to determine if riparian areas are useful for wildlife. I installed camera traps to less-intrusively observe wildlife and compare if streams and riparian areas or terrestrial habitat types are more effective at connecting larger reserves, and if this varies along gradients of development pressure in Maple Ridge and Squamish. Working in partnership with a network of partners, including representatives from the municipalities, First Nations, non-profit organizations, BC Parks, and members of the public, my motivation for this project is to recommend conservation strategies specialized to the interests of these partners and to produce educational materials in an effort to reconnect the public to their natural surroundings.

What is a riparian area?

A riparian area is the habitat type situated between a stream and an upland area. This type of habitat is really special because it shares characteristics of both its neighboring habitat types and is quite an important contributor to the function of the ecosystem as a whole. You might know riparian areas as important providers of human services, such as filtering our drinking water or preventing severe flood damage during storms, but riparian areas also provide necessary services to our natural world, such as regulating stream temperature or providing food and shelter for wildlife. Riparian areas receive a lot of disturbance from both the stream and being at the edge of the terrestrial habitat type. Because of this, the vegetation in riparian areas is constantly being turned over, and they are typically composed of shrubs, small trees, grasses, and yes – lots of brambles (ouch)! This is not always the case, however, as sometimes there are large trees in riparian areas and few understory plants. We called these riparian forests. So, as you can see, there is a lot of variation in the characteristics of a riparian area (Figure C.1). As such, riparian areas are able to support a great deal of biodiversity. Don't be fooled by how small riparian areas might be; they can support a higher level of biodiversity per unit area than most other habitat types.

Figure C.1. Different types of riparian areas.
The picture on the left shows a riparian forest. The picture on the right shows a riparian area dominated by shrubs and small trees.

Why use camera traps?

Camera traps are a useful and minimally invasive way to survey wildlife without the presence of humans. Camera traps (also known as game cameras or trail cameras) are motion sensitive, which means that in a still environment the cameras sit idly. When an animal walks in the camera's frame of view, the camera comes alive and captures photos. The motion sensitivity is typically coupled with detecting a heat differential, such as what would be given off by an animal and not plants, however, this is not always the case (especially in the temperate rainforest of B.C.), and we sometimes get endless photos of branches blowing in the wind. Camera traps are a great way to survey wildlife for long periods of time because they can continue to survey an area while the researchers are doing something else. Even as you're reading this manual now, the cameras are at work! Without the presence of humans, you can learn a lot about an animal's behavior. Photo data can be used to study wildlife behavior, habitat preferences, activity patterns, and much more. You can program the cameras to take photos or videos. The cameras also tell you the time, date, the temperature, and the moon phase. You can program the cameras to take one photo or a burst of photos as it senses motion. For our study, we programmed the cameras to take a rapid burst of 3 photos every time it detects motion. There is a quiet period of 15 seconds between bursts where it doesn't take any photos. We did that to allow the animal to move out of the frame after its picture was taken. We don't want to bias our study by photographing the same individual over and over again. We also programmed the camera to take a picture at noon and midnight every day. These time lapse photos will be helpful for us later on when we are studying the characteristics of the habitat patch, such as stream height, weather patterns, etc.

Data collection

Starting in April 2022, we installed 72 camera traps, half of which are in Maple Ridge and the other half are in Squamish. In each town, we selected 12 camera trap sites, marked on the maps below (Figure C.2).

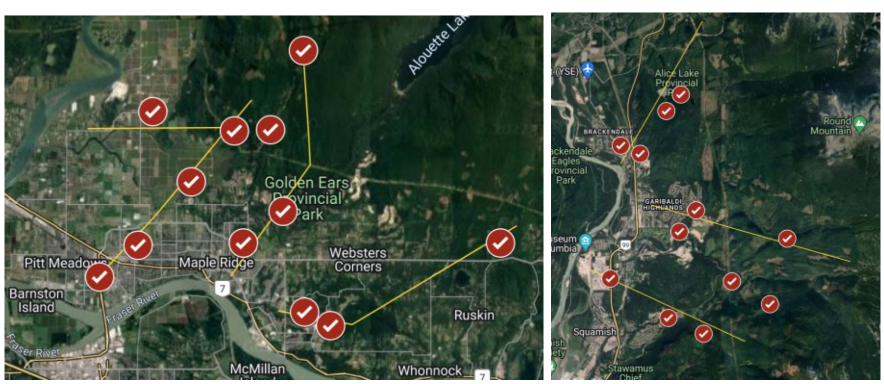


Figure C.2. Maps of all study sites.
The check marks on the map on the left shows the camera trap sites in Maple Ridge. The check marks on the map on the right shows the camera trap sites in Squamish. The yellow lines on the map symbolize an imaginary transect drawn through groupings of camera trap sites, which indicate a potential movement

pathway for wildlife along a development gradient (from the city center towards less developed spaces).

Each camera trap site has a grouping of 3 cameras. Because we want to compare how wildlife use streams vs. riparian areas vs. terrestrial habitat types (which we also call the matrix habitat type), we have installed a camera in each habitat type within a cluster (Figure C.3). So essentially there are 3 cameras per site, 12 sites per town (total of 36 cameras per town), and 2 towns (72 cameras total).

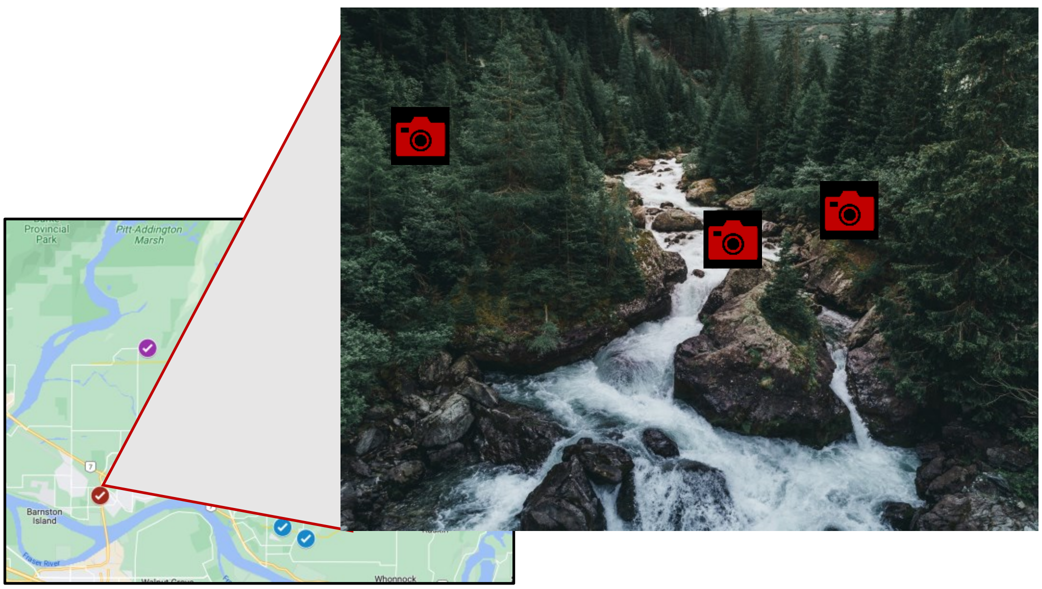


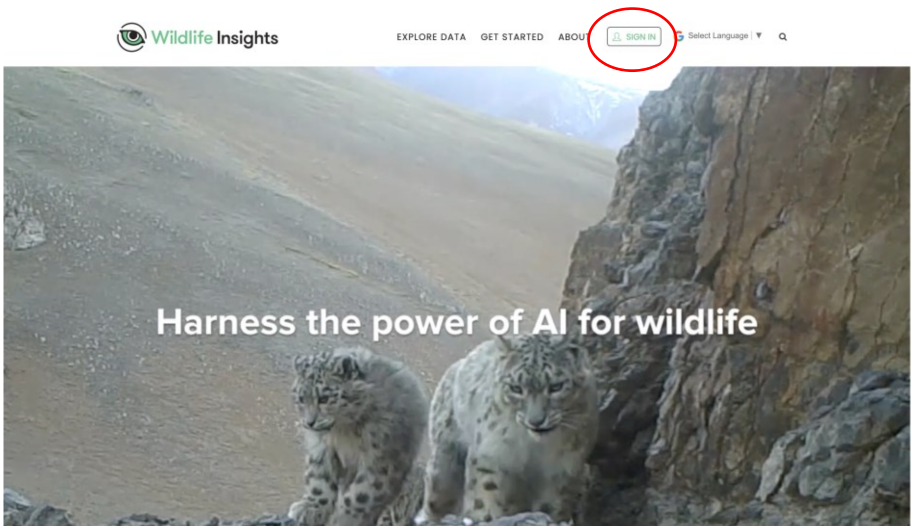
Figure C.3. An example of the camera configuration at a camera trap site. At each site we have installed a camera pointing at the streambed, a camera pointing at the riparian area, and a camera pointing at the surrounding terrestrial habitat patch.

Your role as a work-study student

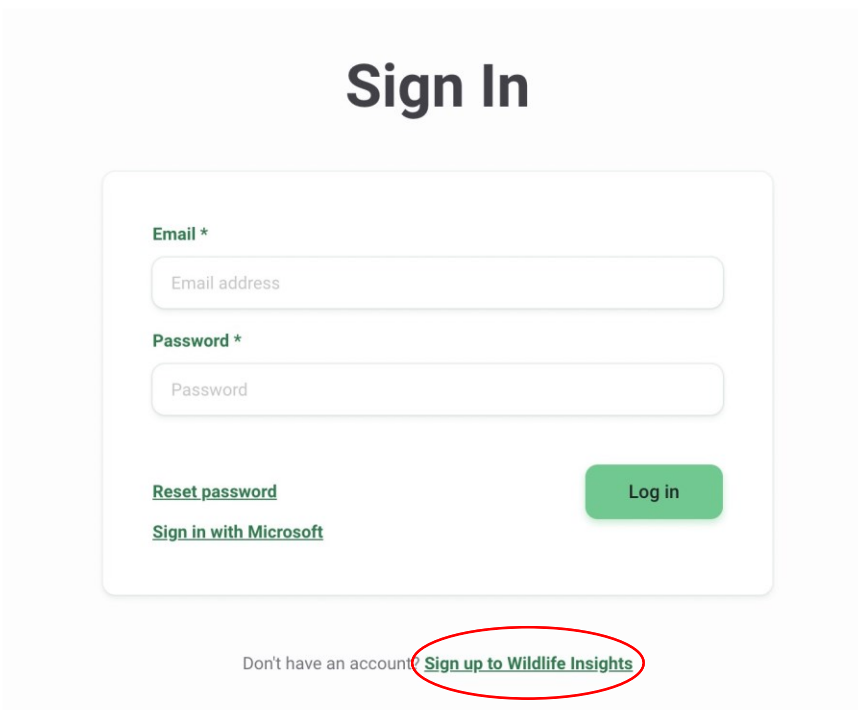
Every few months we will replace the memory cards in our cameras, so there will be a steady stream of photos returning to our lab. Your job is to look through ALL these pictures and identify any animal(s) you see. We have uploaded them to a photo data processing platform, called Wildlife Insights, to help you more easily classify the photos. Wildlife Insights is specifically designed for camera trapping data and is a great collaborative network for camera trapping projects all over the world. If you have some free time, you should check out the other active projects that are using this platform!

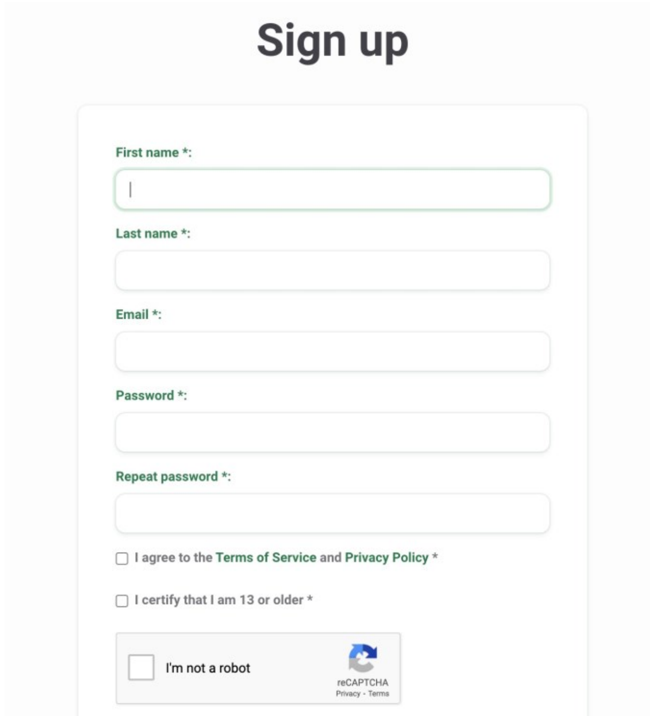
Getting started

You will need to create an account before you can begin identifying photos. Navigate to https://www.wildlifeinsights.org and click the "Sign In" tab.



Follow the prompts to create an account.





Once you have created an account, let me know and I will add you to our project. The project is called "Riparian Corridors."

Identification assignments

I have created two subprojects (Maple Ridge and Squamish) which contain corresponding deployments (noted as the location for each bundle of 3 cameras, also referred to as a camera trap site). Each deployment has a name followed by "Stream," "Riparian," or "Matrix," which indicates which habitat type the camera trap is installed in. The name is the nickname we created for the camera trap site. The table below describes which deployment goes with which subproject (Table C.1). You will be assigned one of the subprojects to work on. You will be tasked with identifying as many of the photos from that subproject as possible.

Table C.1. A list of the deployments within their corresponding subproject.

Next to each deployment, in parenthesis, is its development intensity classification (urban, residential, agriculture, undeveloped).

Maple Ridge	Squamish
Alder (residential)	Britannia (urban)
Blaney (undeveloped)	Dryden (residential)
Codd (agriculture)	Edith (undeveloped)
Green (undeveloped)	FSR (undeveloped)
Highway (urban)	Hop (urban)
Hooge (residential)	Jack (undeveloped)
Kanaka (residential)	Lower Mashiter (urban)
Marian (undeveloped)	Mamquam (undeveloped)
McKenny (residential)	Plateau (residential)
Park (residential)	Ring (undeveloped)
Thornvale (residential/undeveloped)	Stawamus (undeveloped)
Webster (residential)	Upper Mashiter (residential)

You can also use the maps in Figure C.4 and Figure C.5 to situate yourself as you are identifying the photos.

Figure C.4. **A map of Maple Ridge with labeled camera trap sites.**

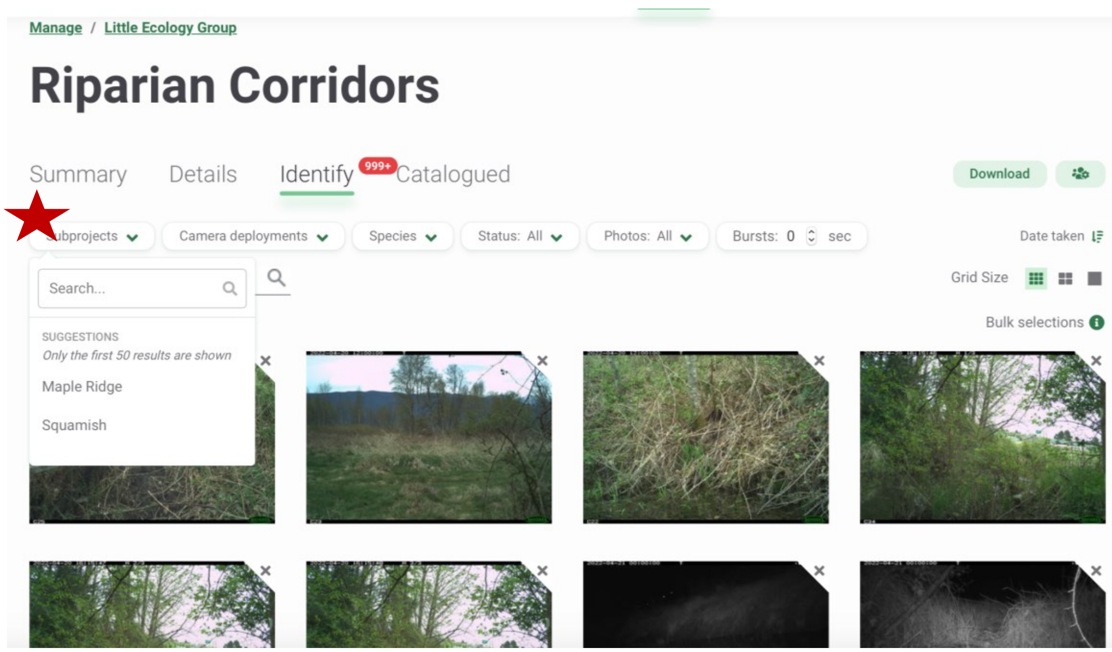
Figure C.5. A map of Squamish with labeled camera trap sites.

Photo identification process

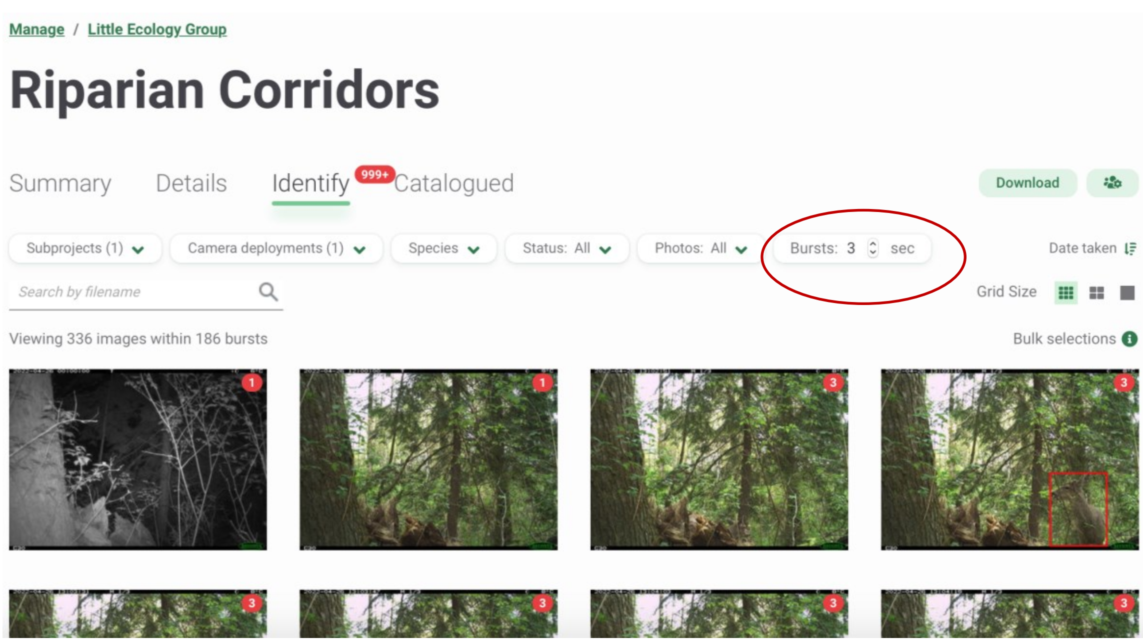
***IMPORTANT NOTE*:** Before you begin, it is important to understand that this job is tedious, and the repetition can be boring. Please make sure that you stay engaged with this work and keep a constant lookout for wildlife in the photos. If you find yourself getting complacent, take a break and come back to it later. The work hours are very flexible!

Once you are logged in, click on the “Manage” tab in the upper righthand menu. Navigate to our project (“Riparian Corridors”). In the summary section of our project, you can find a map of all our deployments in both subprojects. You can also see some summary statistics on the photo data themselves. To identify photos, click on the “Identify” section. This will take you to all the photos that have yet to be classified.

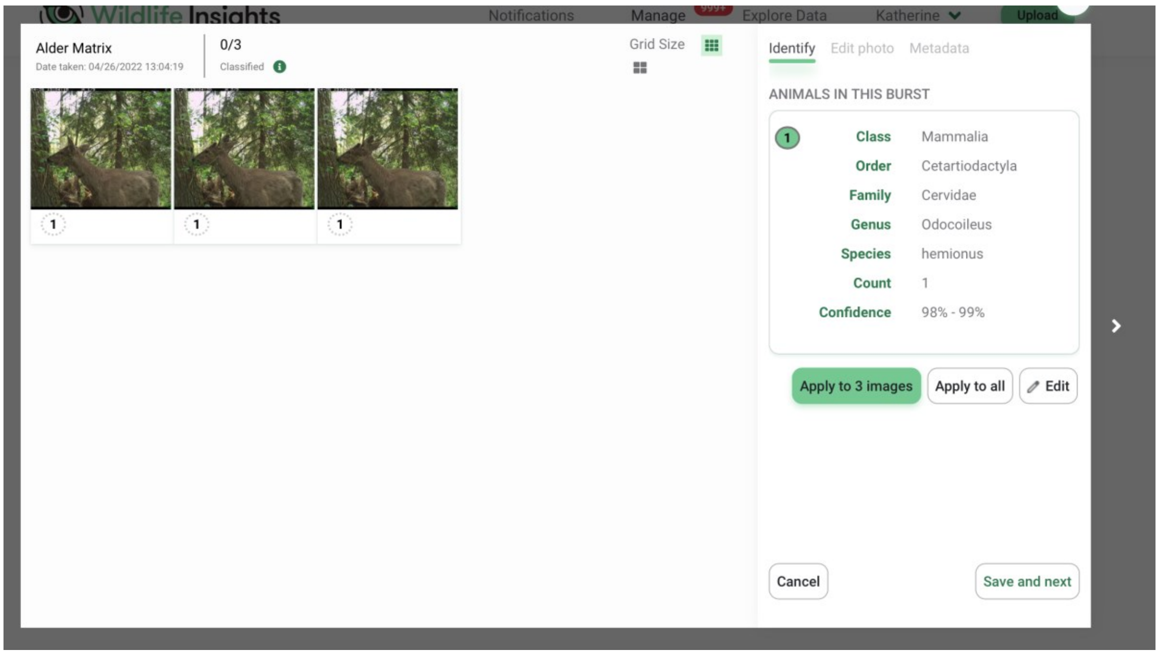
Before you begin classifying photos, select your subproject in the corresponding filter at the midsection of the page.



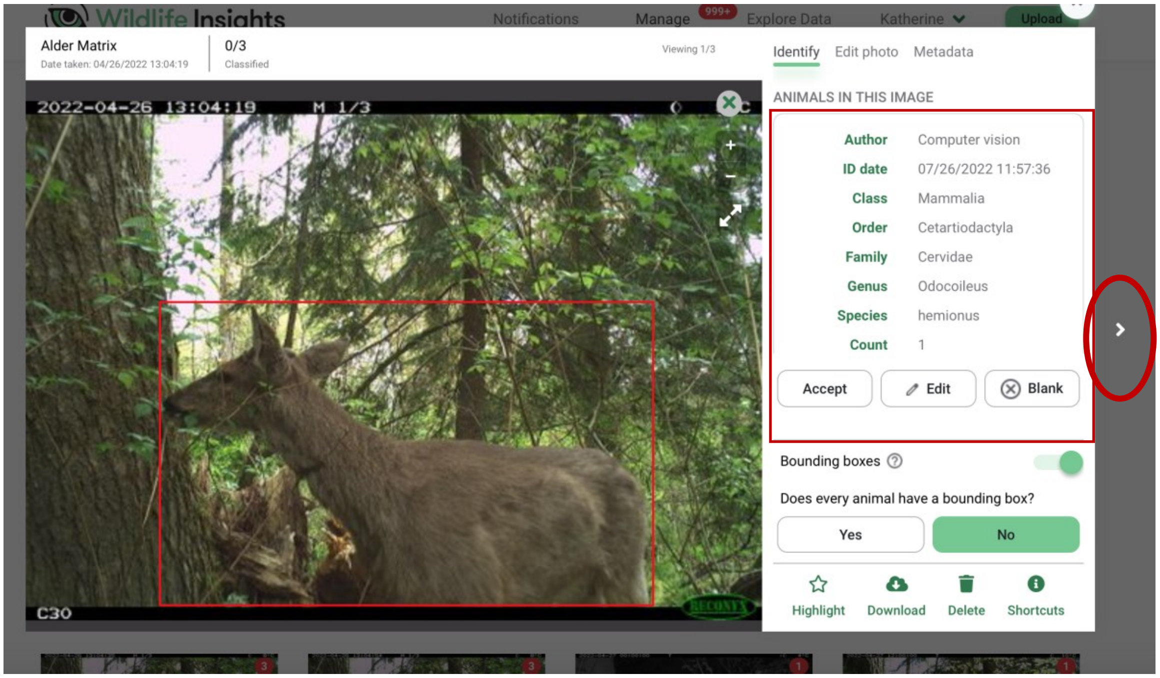
***IMPORTANT NOTE*:** The cameras are set up to take a rapid burst of 3 photos every time there is movement. You will need to group the bursts so that you can identify all the photos in a burst. To do that, set the "Bursts" filter to 3 seconds.



Now you are ready to identify the photos! Click on the first burst in your list. A panel should appear similar to this one below.

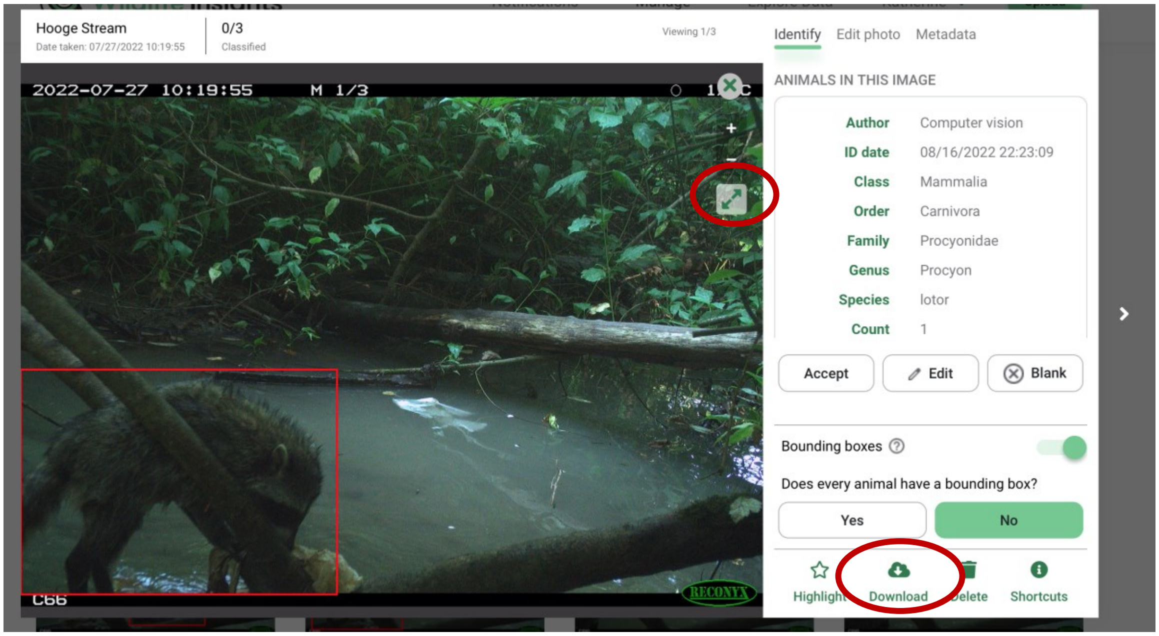


Double click on the first image in the burst and use the right and left arrows to see all images in the burst up close.



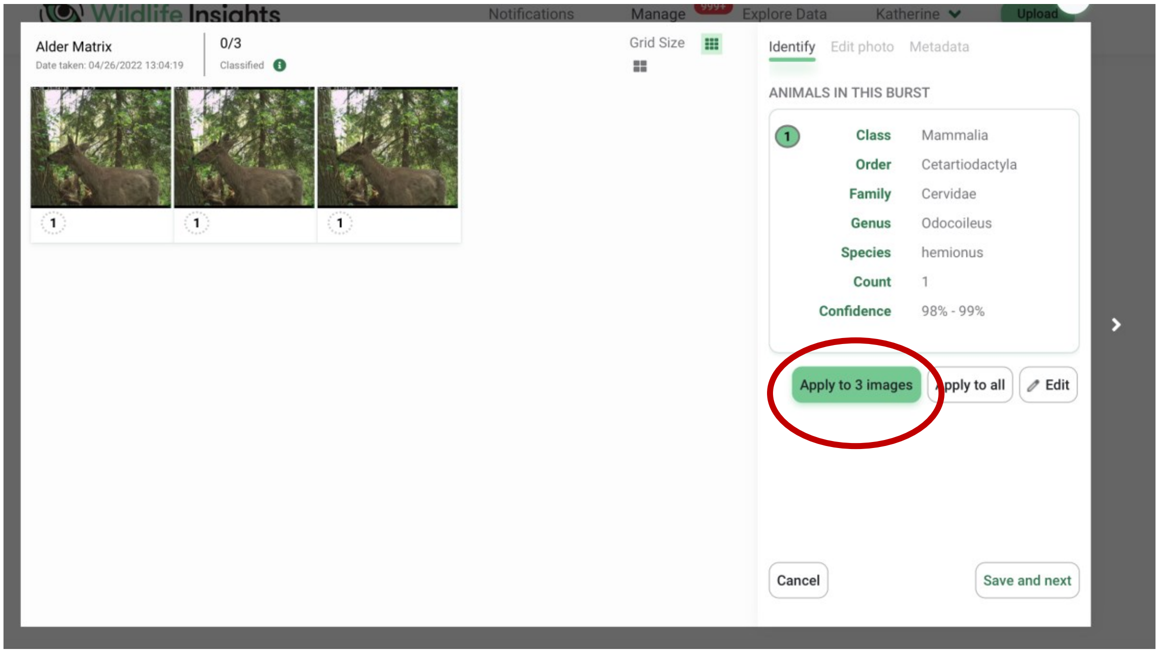
You can see how when you click on an image with an animal in it, there is a red box around it. That's because Wildlife Insights has some artificial intelligence features. The computer has guessed the type of animal in the red box, which you can see on the right side of your screen (shown in the picture above). In this example, the computer correctly identified the animal in the photo as a mule deer.

If the images are difficult to see, you can click on the "View high resolution image" button in the upper righthand corner of the image or you can click on the "Download" button at the bottom righthand corner of the identification panel.

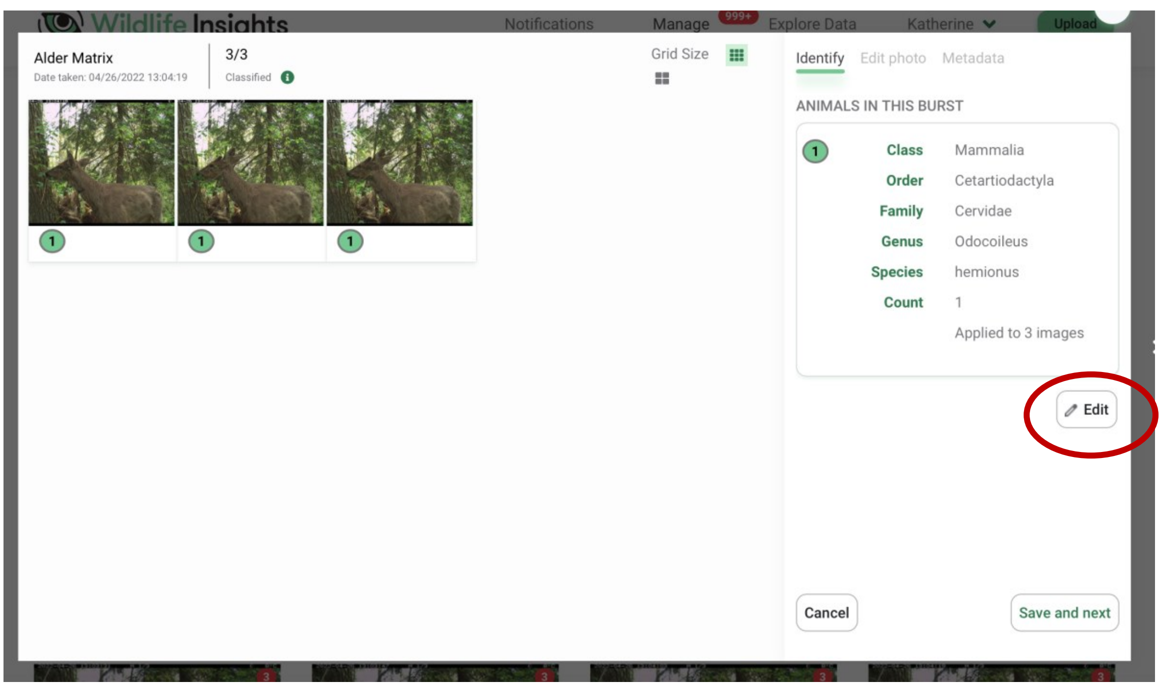


Once you are done scrolling through the photos in your burst, click the "X" button in the upper corner of the photo and return to the panel with the three photos presented to you.

Be sure that the number of individuals in the picture is accurately reflected in the "Count" section of the classification. If you are satisfied with what the computer selected, hit the button that says, "Apply to 3 Photos."



Once you have done that, hit the edit button because we need to add a note about the animal's behavior and movement pattern to each burst.



Navigate to the "Behavior" section. We are using that as our notes section for behavior, however, it is VERY important that we follow a code when recording the animal's behavior. I will be processing this data in R later on and correcting for typos can be quite time consuming. Please use the following code to record the behaviors of the animals:

Behavior List (in 'Behavior' section)

*Codes are in all UPPERCASE

Here is the code to use:

ALT = alert

CLB = climbing

DIG = digging

FLY = flying/gliding

EAT = foraging/eating

GRM = grooming

INT = interacting (with each other or with the camera)

JMP = jumping

SIT = sitting/standing/lying

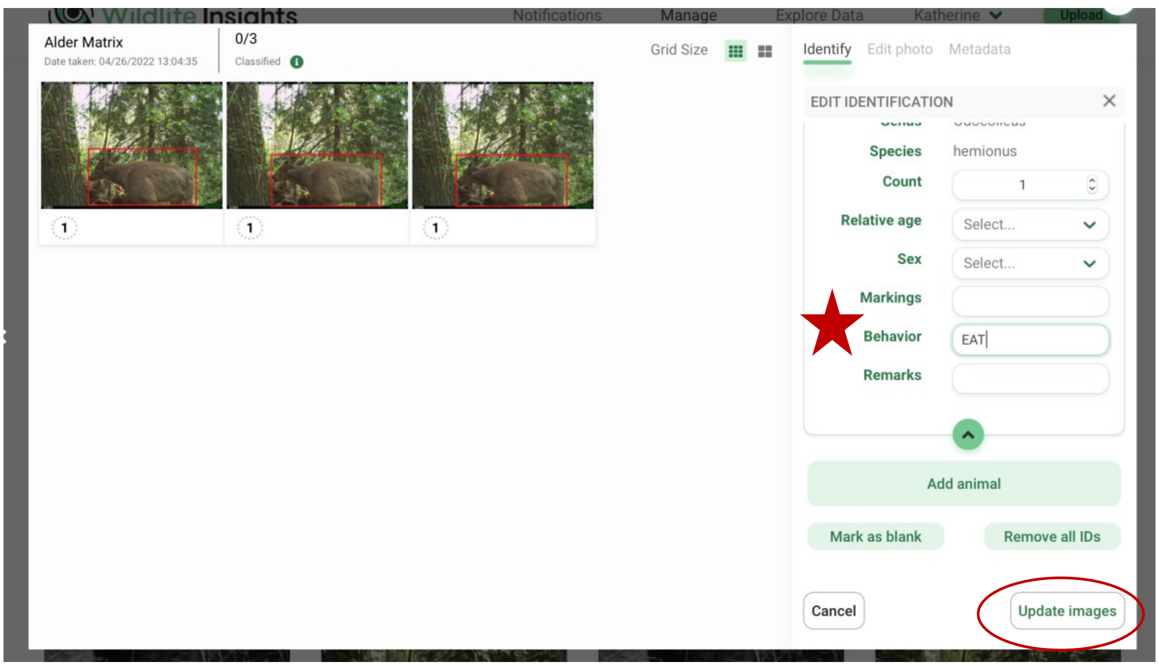
RUN = running/walking

SWM = swimming

OTR = other

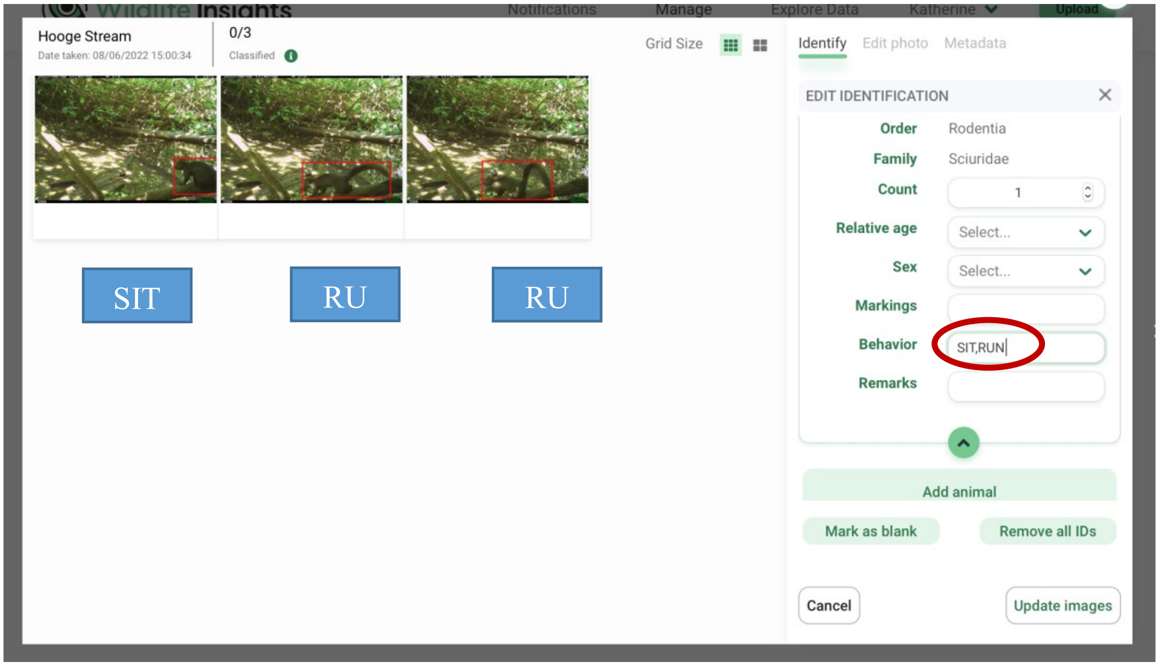
IMPORTANT NOTE: You should constantly refer to this list to remind yourself of all the behavior choices available to you. It is easy to memorize a few codes and just use those when there are better options in this list. If you find a behavior not represented on this list, please let me know.

For the most part, the animal will be exhibiting the same behavior in all three photos within a burst. In this case, you will enter the code for the behavior you see into the “Behavior” section in the identification. Be sure that this ID gets applied to all three photos in the burst.



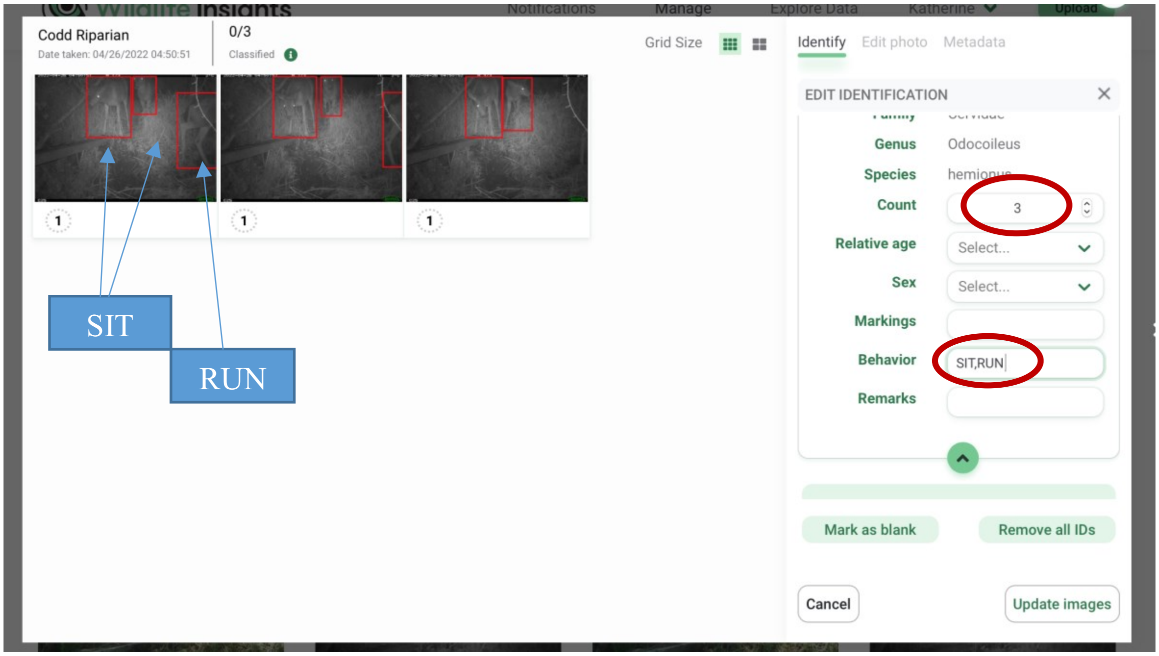
*Identify each behavior you see. If within a burst of photos the animal changes behavior, create one ID for all three photos in the burst and record all behaviors in the ‘Behavior’ section, separated by a comma and NO spaces.

Example: In ‘Behavior’ section – SIT,RUN



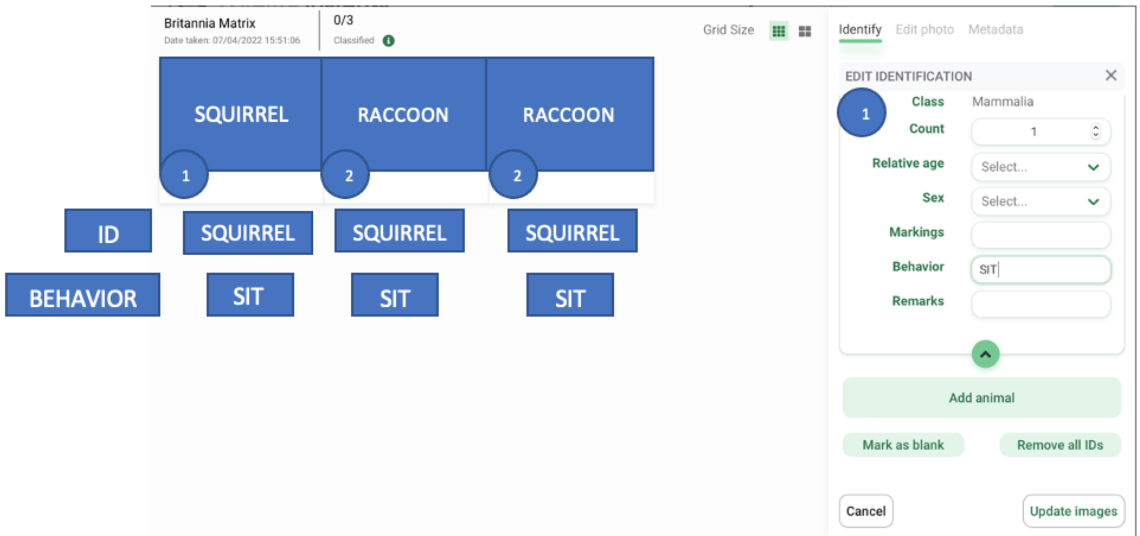
If there is more than one animal (of the same species) in the same picture exhibiting a different behavior, separate the behaviors by a comma and NO spaces.

Example: In 'Behavior' section – SIT,RUN. Adjust the 'Count' section to 3 individuals.

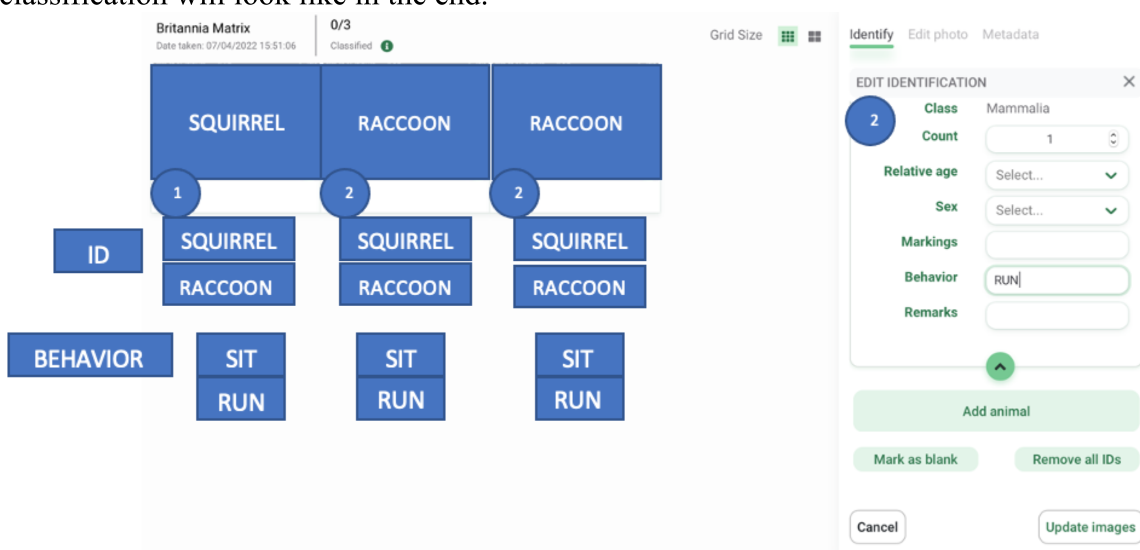


If there are two animals of different species in the frame, make two different records (one for each animal) and report the appropriate behavior for each individual. Be sure to apply the IDs to all three photos in the burst, even if the animals only appear in one or two of the photos.

The first record should describe the behavior of the first animal. The ID should be applied to all three images in the burst.



The second record should describe the behavior of the second animal. The ID should be applied to all three images in the burst. This is what the completed classification will look like in the end.



Before you move on, have a look at the direction that the animals are moving in. Find the "Remarks" section, located below where you recorded the animal's behavior.

This is where you will be recording the direction of movement. For the animals walking in the stream, refer to Appendix A for a list of all streams and which direction is upstream versus downstream.

Please use the following code to record the direction of movement for the animals:

Direction List (in 'Remarks section)

*Codes are in all UPPERCASE

UPS = Upstream (stream only)

DWN = Downstream (stream only)

STL = Still/Not moving

TWD = Towards camera

AWY = Away from camera

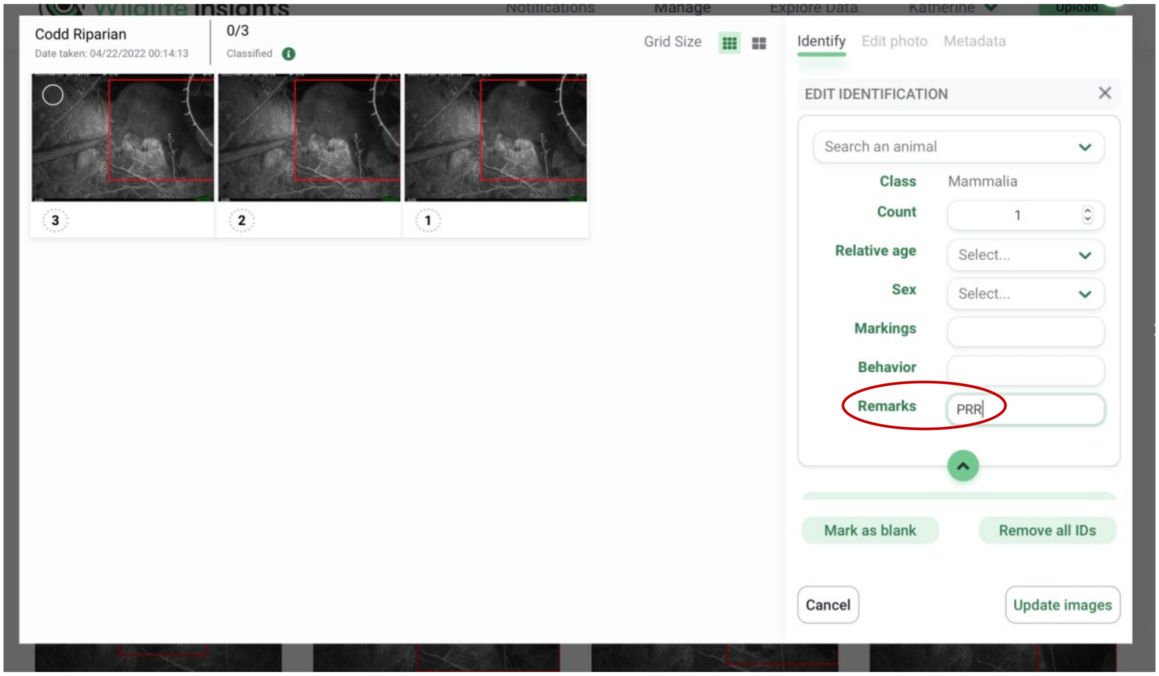
PRL = Perpendicular to camera, walking from the right of the camera to the left (land only)

PRR = Perpendicular to camera, walking from the left of the camera to the right (land only)

HGH = Vertically upward (climbing up)

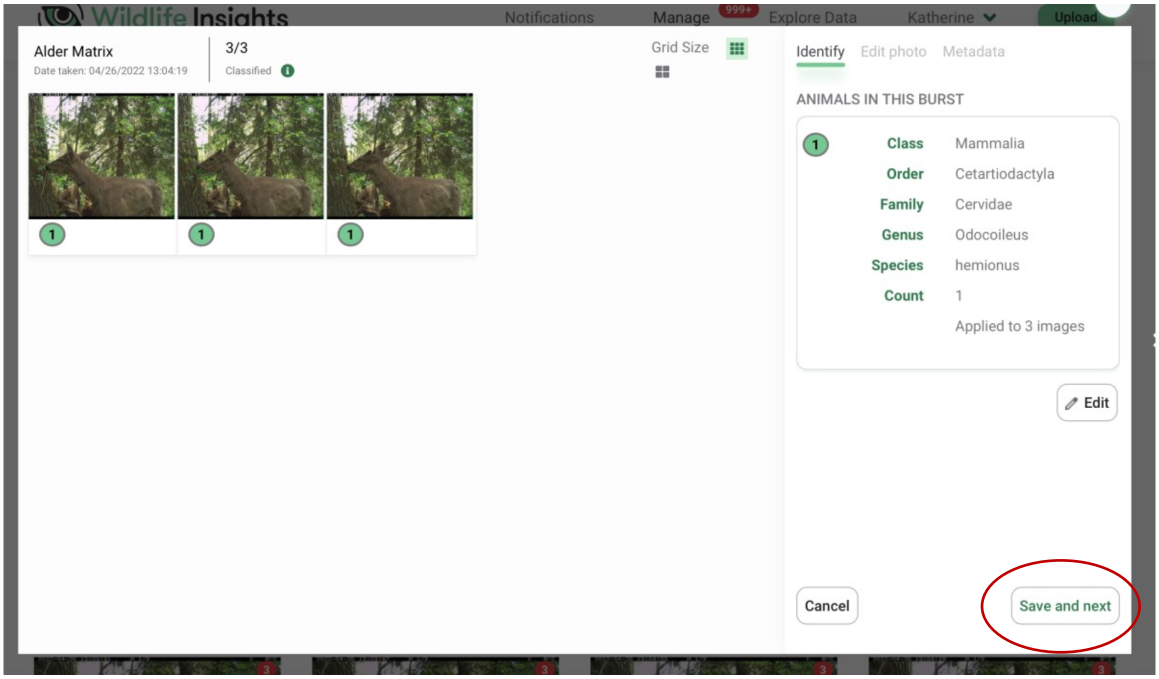
LOW = Vertically downward (climbing down)

Follow the same pattern of identification as you did for the animal behaviors.



Once you are done, click the “Update images” button.

To finish, hit the “Save and Next” button. Great job, you have just identified your first image!

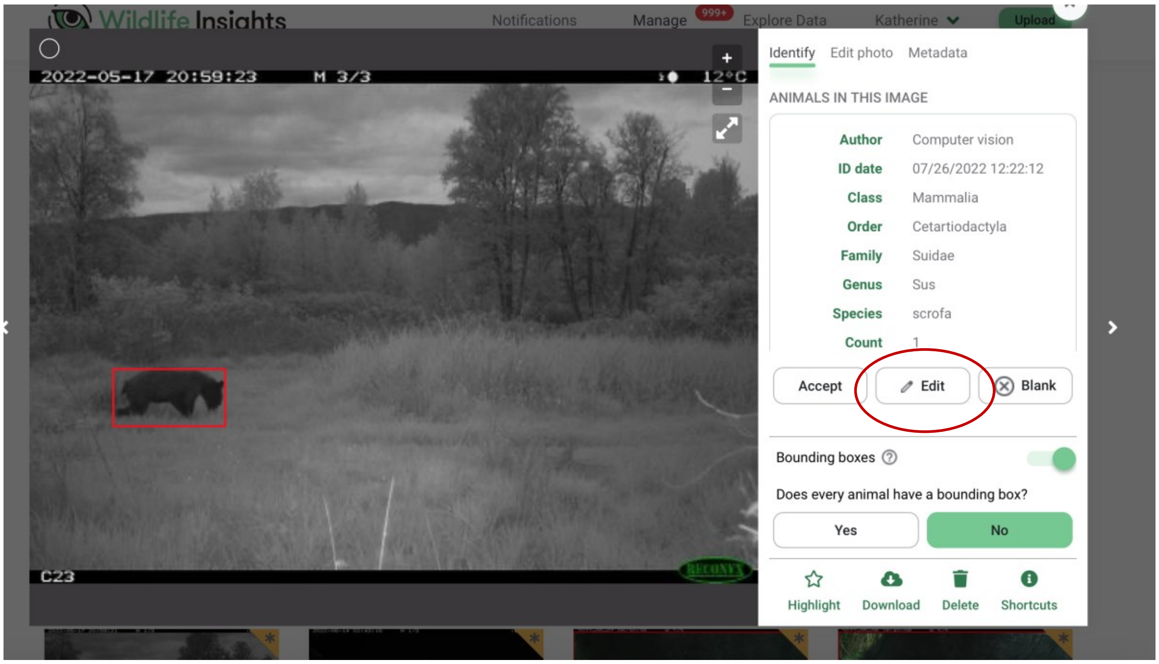


IMPORTANT NOTE: Make sure you apply each ID to all three photos within a burst even if they do not appear in all three photos. Later, I will be using bursts as a single count of animal detection, so I need them to be the same animal(s) in all three photos to not oversaturate the data with blank images. If any of this is unclear, I'm happy to explain in more detail!

IMPORTANT NOTE: Since we need to ID all photos in the burst with the same animal(s), please never use the "Species" filter in the top panel. This filter will only pull out photos that the computer detects the species in it. It will not bring the other photos in the burst with it.

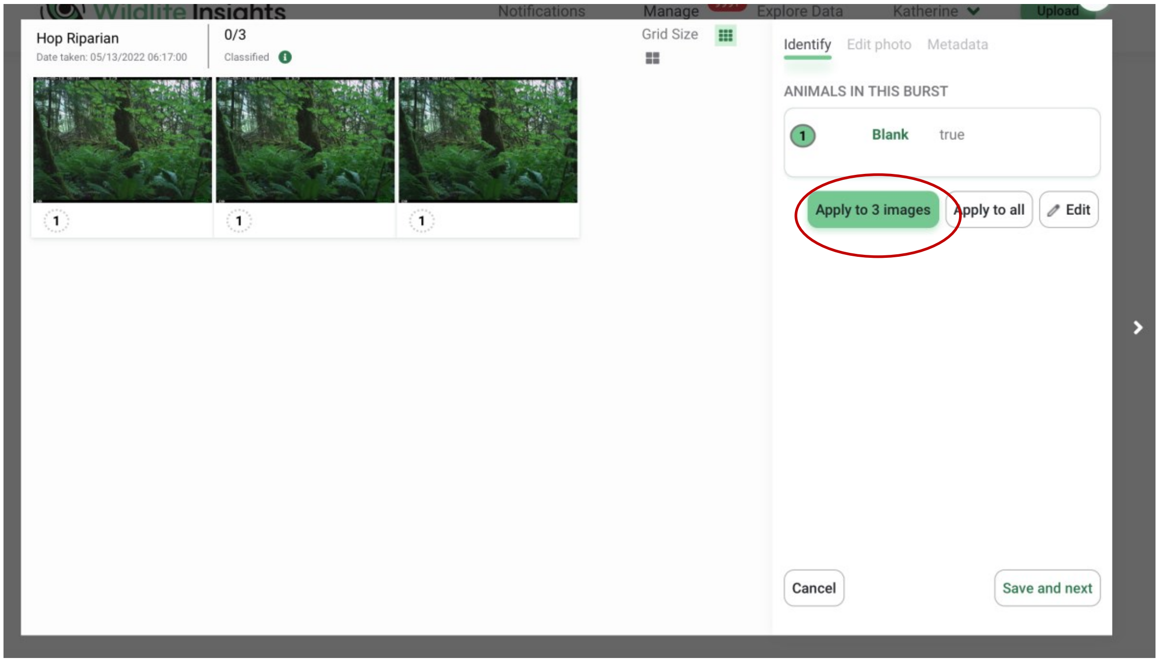
Image identification difficulties

Sometimes the computer's guess is incorrect, or incomplete. This is why we need you to go through every photo! If the ID is wrong, as observed from the photo below (this is clearly not a wild boar…), hit the edit button and repeat the same process as above to correctly identify the animal(s) in the photo. Be sure to remember to add the animal behavior in the “Behavior” section for each behavior observed for each individual. Also, don’t forget to add each animal’s direction of movement. When you have correctly identified the animals in the photo, click “Update Images” and then hit “Save and Next.”

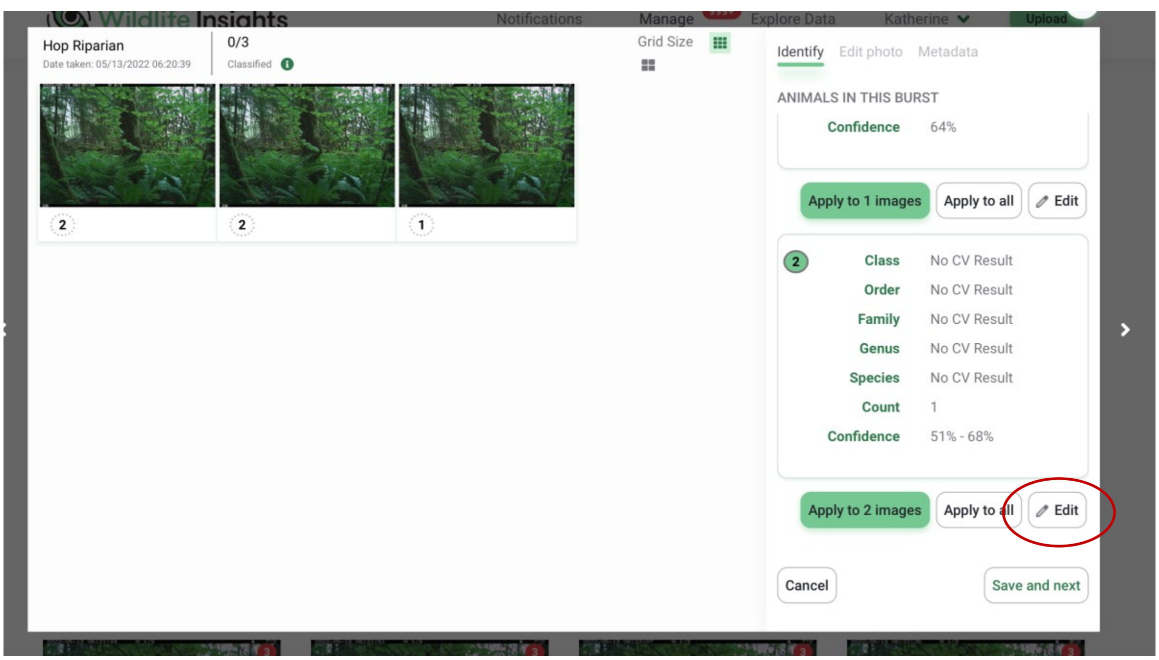


Dealing with blank images

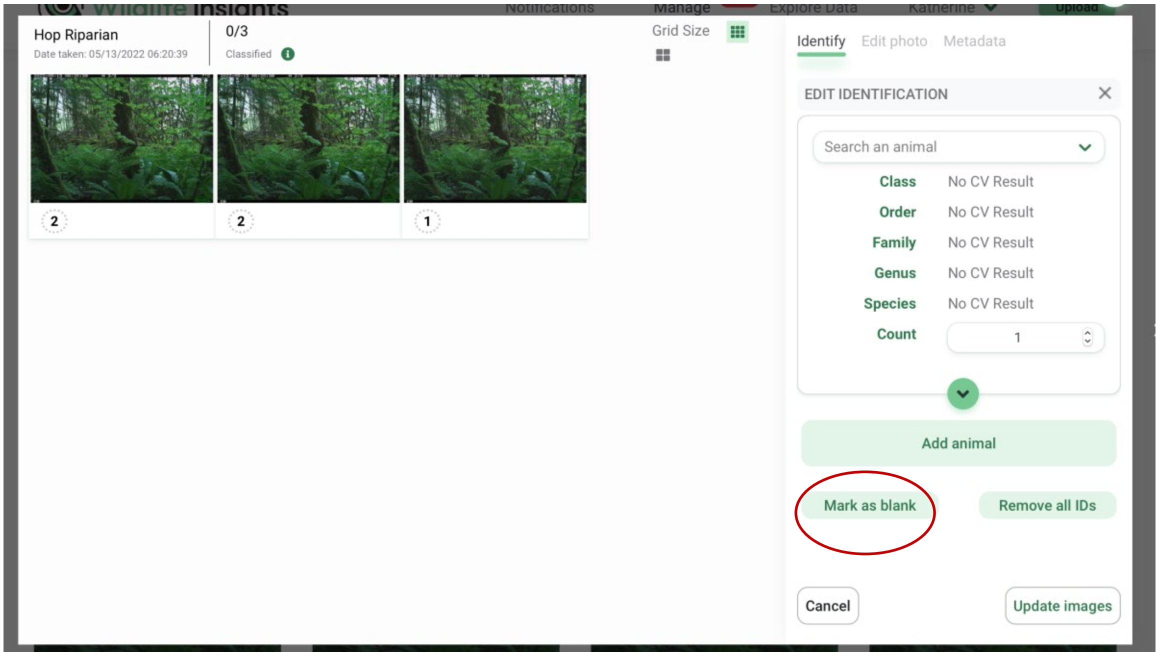
Unfortunately, a lot of the time you will be looking at images with no animals in them. Sometimes the cameras malfunction and capture 20,000 images of leaves blowing in the breeze. If this is the case and the computer has marked a burst of images as blank, you can hit the “Apply to 3 images” button and then hit “Save and Next.”



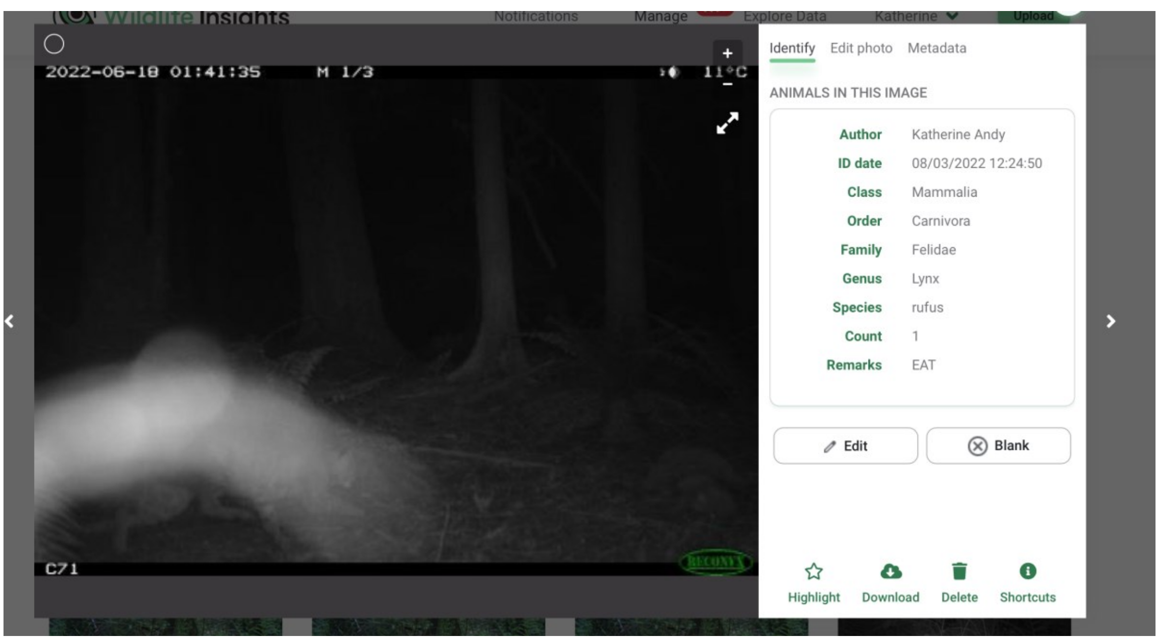
If the computer guessed incorrectly, or guessed this "No CV Result" message shown below, you need to edit the ID.



When you click on the "Edit" button, click on the button that says, "Mark as Blank." Be sure that all images in the burst get the same ID if all images are blank.



Be careful not to get into the groove of marking images as blank. Sometimes animals are present but are really hard to see. For example, can you spot the bobcat in the image below? Take your time going through the photos – don't rush! This job can be tedious. Take lots of little breaks to keep your mind engaged with this work.



Final notes

- Take some time to familiarize yourself with the mammals in the lower half of British Columbia. There are some really great ID guides in the lab that you should use as a reference. There are also two great resources called the BC Species and Ecosystem Explorer (BCSEE) and the BC Conservation Data Centre iMap (BCCDC iMap), which tell you all about the wildlife in BC, where they're found, and what their ecological statuses are. See also the "Differentiating Mammals of British Columbia" document provided with this manual.

- If you are ever unsure of any photos, whether ID related or whether there is something present or not, flag it and I will help you figure it out! There isn't a great way to flag an item, so I would suggest writing down the camera trap location and the date/time of the burst so I can go back through and find it later.

- Please do not guess on an ID. Classify only as far as you know. If that is just to the family name, that is fine. Flag it and I will go through it later. For birds, if you get as far as the family name, that is great. Birds are really difficult to ID, and for right now, they are not the focus of this study.

- Please notify me if there are any abnormalities in the data (i.e., duplicates). It's possible that I made an error during the uploading process.

- Should you see humans in a photo burst, do not look at or process those. Leave them for me to deal with.

- Do not show other people the pictures with humans in them and do not save those pictures to your device.

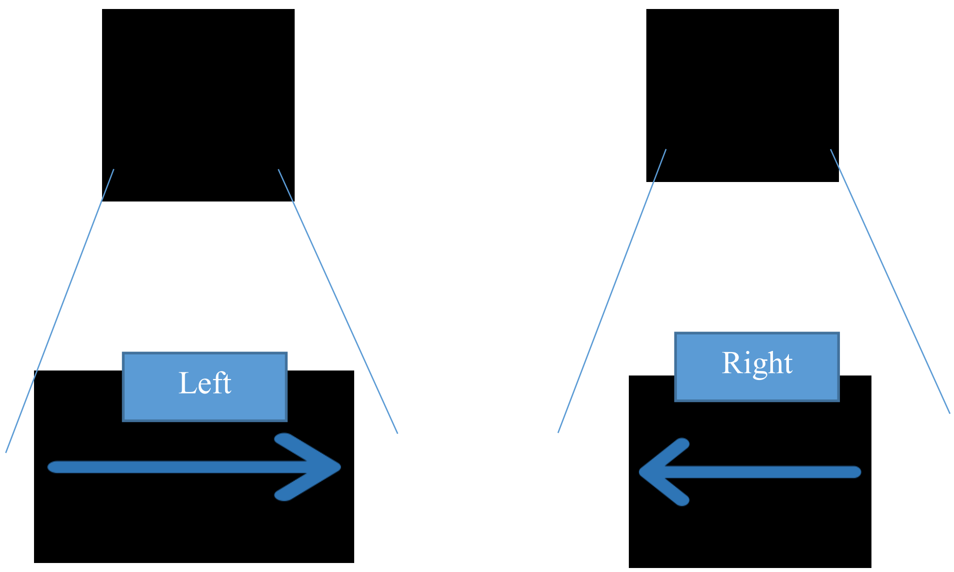
- If you find any cool photos, upload them to the lab's "lab-website-social-media" Slack channel! We would love to feature it on social media/share with the other lab members.

- Don't hesitate to reach out to me if you have any questions or concerns.

Supplementary materials

Supplement A.

The following table describes the general direction the water is flowing at each stream. Note: if the direction is right, the water is flowing from the left of the camera to the right. If the direction is left, the water is flowing from the right of the camera to the left. Remember that you will be looking through the camera lens, so imagine that you are the camera in the diagram below, looking across at the arrow.



Site Name	Stream Direction
Maple Ridge	
Alder	Right
Blaney	Right
Codd	Right
Green	Right
Highway	Right
Hooge	Left (before 6/17), Right (after 6/16)
Kanaka	Left
Marian	Right
McKenny	Left
Park	Left
Thornvale	Left
Webster	Right
Squamish	
Britannia	Right
Dryden	Right
Edith	Left
FSR	Left
Hop	Left
Jack	Right
Lower Mashiter	Right
Mamquam	Left
Plateau	Left
Ring	Right
Stawamus	Right
Upper Mashiter	Left

Supplement B.

The list below are the dates I was in the field:

- April 20, 2022
- April 22, 2022
- April 25, 2022
- May 9, 2022
- May 11, 2022
- May 12, 2022
- May 13, 2022
- May 16, 2022
- June 15, 2022
- June 16, 2022
- June 17, 2022
- June 20, 2022
- June 22, 2022
- June 23, 2022
- June 27, 2022
- June 29, 2022
- July 4, 2022
- July 6, 2022
- July 7, 2022
- July 8, 2022
- July 11, 2022
- July 14, 2022
- July 15, 2022
- August 11, 2022
- August 12, 2022
- August 15, 2022
- August 16, 2022
- August 17, 2022
- November 2, 2022
- November 5, 2022
- November 7, 2022
- November 11, 2022
- November 12, 2022
- November 14, 2022
- November 16, 2022
- November 19, 2022
- November 23, 2022
- February 14, 2023
- February 20, 2023
- February 21, 2023
- February 22, 2023
- February 23, 2023
- February 24, 2023
- March 4, 2023
- March 5, 2023
- April 12, 2023
- May 9, 2023
- May 10, 2023
- May 11, 2023
- May 12, 2023
- May 13, 2023
- May 15, 2023
- May 16, 2023
- June 5, 2023
- June 14, 2023
- June 15, 2023
- June 16, 2023

Appendix D.

Supplementary information from the mixed-variable joint species distribution model

Mixed-variable joint species distribution model results

Table D.1. **A table showing how well the mixed-variable joint species distribution model explained detections of each taxonomic group.**

RMSE is the root mean square error. SR2 is the pseudo-R2 squared Spearman correlation between observed and predicted values. O.AUC represents the area under the curve. O.TjurR2 is Tjur's R2. Both AUC and Tjur's R2 evaluate how well species occurrences are predicted. C.SR2 and RMSE are the root mean square error and pseudo-R2 for cases conditional on presence.

Taxonomic Group	RMSE	SR2	O.AUC	O.TjurR2	C.SR2	C.RMSE
American black bear	3.23	0.40	0.85	0.42	0.24	4.96
American mink	0.71	0.06	0.82	0.25	0.09	2.63
Bobcat	0.83	0.26	0.81	0.31	0.37	1.63
Coyote	3.18	0.42	0.83	0.40	0.46	4.71
Domestic cat	0.85	0.64	0.97	0.72	0.46	3.35
Domestic Dog	2.46	0.15	0.78	0.32	0.30	5.16
Douglas's squirrel	2.56	0.28	0.82	0.35	0.29	4.95
Gray squirrels	15.91	0.34	0.77	0.36	0.56	24.39
Mule deer	2.13	0.44	0.87	0.46	0.47	4.07
North American river otter	0.55	0.41	0.80	0.41	0.79	2.93
Northern raccoon	6.44	0.41	0.83	0.42	0.39	9.32
Snowshoe hare	1.76	0.34	0.91	0.51	0.54	6.00
Rats and Mice	15.16	0.26	0.80	0.41	0.58	31.64

Table D.2. A 95% credible interval for each taxonomic group and environmental predictor variable used in the mixed-variable joint species distribution model. Reported values are 50% (5%, 95%).

Taxonomic Group	Intercept	Maximum NDVI	Elevation	Road Distance	Summer Streambank Height	Recorded Salmon Presence	Spring	Summer
American black bear	-0.77 (-1.48, -0.11)	0.5 (0.16, 0.84)	-0.98 (-1.3, -0.65)	0.24 (0.12, 0.33)	0.55 (-0.76, -0.37)	1.24 (0.59, 1.92)	0.81 (0.48, 1.13)	0.63 (0.42, 0.85)
American mink	-3.55 (-5.52, -1.79)	-0.29 (-1.35, 0.44)	-0.87 (-1.77, 0.01)	0.08 (-0.29, 0.4)	0.87 (0.6, 1.2)	-1.3 (-2.24, -0.23)	-0.7 (-1.56, 0.02)	0.52 (-0.01, 1.09)
Bobcat	-4.92 (-6.4, -3.65)	-0.26 (-0.78, 0.29)	-0.65 (-1.49, 0.08)	0.15 (-0.06, 0.37)	0.34 (0.06, 0.66)	2.27 (0.8, 3.81)	-1.61 (-2.35, -0.92)	-0.41 (-0.79, -0.02)
Coyote	-1.75 (-2.59, -1.08)	-1.63 (-2.33, -0.46)	-0.36, -1.22, 0.46)	0.01, -0.14, 0.15)	-0.12 (-0.63, 0.47)	0.75 (-0.28, 1.95)	0.01 (-0.25, 0.31)	-0.17 (-0.38, 0.05)
Domestic cat	-8.38 (-12.88, -4.9)	-11.34 (-15.34, -8.73)	6.27 (4.05, 9.8)	-1.27 (-2.28, -0.49)	1.74 (-0.1, 3.63)	7.44 (2.88, 13.06)	0.68 (0.11, 1.29)	-0.82 (-1.47, -0.2)
Domestic dog	-4.06 (-5.38, -2.84)	-0.63 (-1.16, -0.12)	-0.44 (-1.06, 0.13)	-0.12 (-0.34, 0.09)	0.27 (-0.04, 0.58)	1.23 (0.19, 0.11)	1.09 (0.77, 1.4)	0.21(-0.21, 0.66)
Douglas's squirrel	-3.43 (-5, -2.06)	-1.06 (-1.54, -0.61)	1.09 (0.62, 1.64)	0 (-0.22, 0.18)	0.82 (0.5, 1.16)	1.28 (0.24, 2.42)	-1.72 (-2.37, -1.18)	-0.75 (-1.04, -0.49)
Gray squirrels	-1.93 (-3.79, -0.17)	-8.25 (-8.88, -7.66)	5.87 (4.64, 7.09)	-0.93 (-1.06, -0.8)	0.63 (-0.7, 2.00)	5.28 (1.96, 8.89)	-0.37 (-0.51, -0.23)	-0.01 (-0.12, 0.1)

Mule deer	-2.94 (-3.9, -1.98)	2.59, 1.75, 3.56)	-1.37, -2.12, -0.73)	0.41 (0.22, 0.61)	-1.09 (-1.62, -0.65)	0.32 (-0.9, 1.57)	1.01 (0.55, 1.53)	0.31 (-0.01, 0.62)
North American river otter	-0.63 (-2.54, 1.13)	-0.91 (-1.96, -0.04)	0.32 (-0.57, 1.25)	0.24 (-0.26, 0.66)	0.66 (0.06, 1.29)	-2.64 (-4.13, -1.09)	0.19 (-0.66, 0.94)	-0.09 (-0.7, 0.45)
Northern raccoon	-1.05 (-1.67, -0.4)	-1.38 (-1.66, -1.09)	-0.63 (-1.12, -0.15)	0.16 (0.02, 0.31)	0.2 (-0.14, 0.6)	-0.52 (-1.46, 0.41)	-0.56 (-0.74, -0.37)	0.1 (-0.04, 0.25)
Snowshoe hare	-1.43 (-3.97, 0.67)	-4.75 (-6.27, -2.59)	4.67 (2.65, 6.44)	-0.38 (-0.83, 0.1)	0.69 (-0.63, 2.11)	0.38 (-3.15, 4.27)	1.85 (1.07, 2.52)	-1.21 (-1.78, -0.61)
Rats and Mice	-5.37 (-7.21, -3.55)	-8.65 (-9.68, -7.65)	6.12 (4.69, 7.6)	-1.1 (-.137, -0.83)	1.14 (-0.08, 2.5)	4.94 (1.7, 8.53)	-0.5 (-0.69, -0.32)	0.23 (0.08, 0.37)

Table D.2 (cont.). **A 95% credible interval for each taxonomic group and environmental predictor variable used in the mixed-variable joint species distribution model. Reported values are 50% (5%, 95%).**

Taxonomic Group	Winter	Riparian	Stream	Camera-Days	Average Visibility Distance
American black bear	-1.99 (-2.5, -1.58)	0.27 (0.08, 0.47)	-0.47 (-0.67, -0.26)	0 (-0.01, 0.01)	0.24 (0.17, 0.32)
American mink	0 (-0.61, 0.55)	0.51(-0.14, 1.14)	1.4 (0.66, 2.11)	0 (-0.01, 0.02)	-0.57 (-0.84, -0.32)
Bobcat	0.11 (-0.28, 0.45)	-0.04 (-0.47, 0.39)	0.01 (-0.4, 0.41)	0.03 (0.02, 0.04)	-0.02 (-0.18, 0.16)
Coyote	0.31 (0.13, 0.52)	-0.1 (-0.3, 0.09)	-0.6 (-0.86, -0.38)	0.01 (0.01, 0.02)	0.33 (0.25, 0.42)
Domestic cat	0.51 (0.04, 0.99)	0.53 (0.12, 0.96)	-0.19 (-1.1, 0.79)	-0.02 (-0.04, -0.01)	-1.03 (-1.58, -0.63)
Domestic dog	0.22 (-0.11, 0.6)	-0.25 (-0.64, 0.09)	0.08 (-0.28, 0.4)	0.02 (0.01, 0.03)	0.47 (0.34, 0.61)
Douglas's squirrel	-0.82 (-1.09, -0.54)	0.07 (-0.22, 0.36)	-0.49 (-0.81, -0.16)	0.03 (0.01, 0.04)	-0.56 (-0.72, -0.42)
Mule deer	0.15 (-0.19, 0.48)	-0.26 (-0.55, 0.06)	-0.94 (-1.26, -0.63)	0.01 (0, 0.02)	0.49 (0.37, 0.61)
North American river otter	-0.54 (-1.19, 0.13)	-0.52 (-1.52, 0.43)	1.48 (0.56, 2.4)	-0.03 (-0.05, -0.02)	-0.92 (-1.43, -0.39)
Northern raccoon	-0.23 (-0.38, -0.07)	-0.28 (-0.47, -0.09)	1.2 (1.05, 1.36)	0.01 (0.01, 0.01)	-0.52 (-0.62, -0.44)
Snowshoe hare	0.5 (0.13, 0.89)	-1.87 (-2.4, -1.28)	-2.62 (-3.36, -1.93)	-0.03 (-0.04, -0.01)	-0.58 (-0.99, -0.18)
Rats and Mice	-0.89 (-1.09, -0.7)	-0.06 (-0.29, 0.16)	0.19 (-0.08, 0.47)	0.02 (0.02, 0.03)	-1.7 (-1.9, -1.45)
Gray squirrels	-0.24 (-0.36, -0.11)	-0.58 (-0.72, -0.45)	0.19 (0.04, 0.33)	0 (0, 0.01)	-0.69 (-0.76, -0.61)

Species co-occurrence results from the mixed-variable joint species distribution model

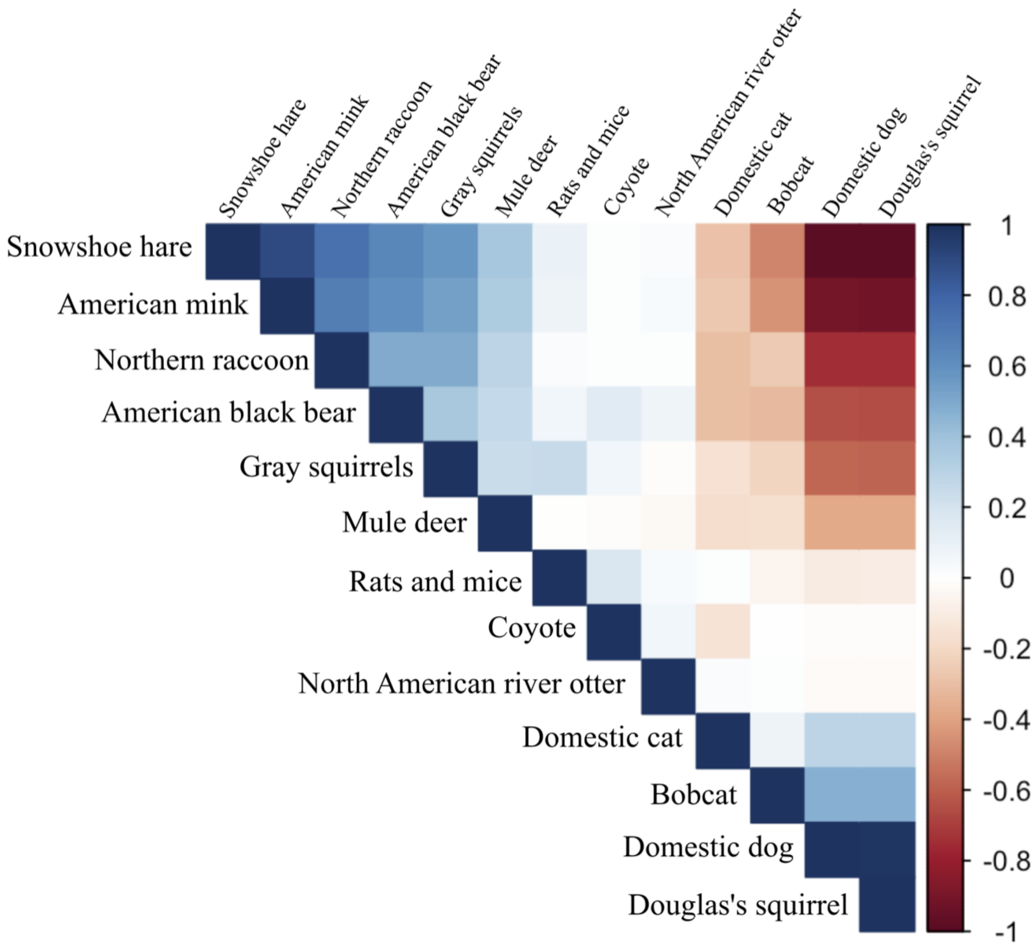


Figure D.1. Species co-occurrences among the mammalian community. This plot was generated at the study location level (i.e., Squamish and Maple Ridge).

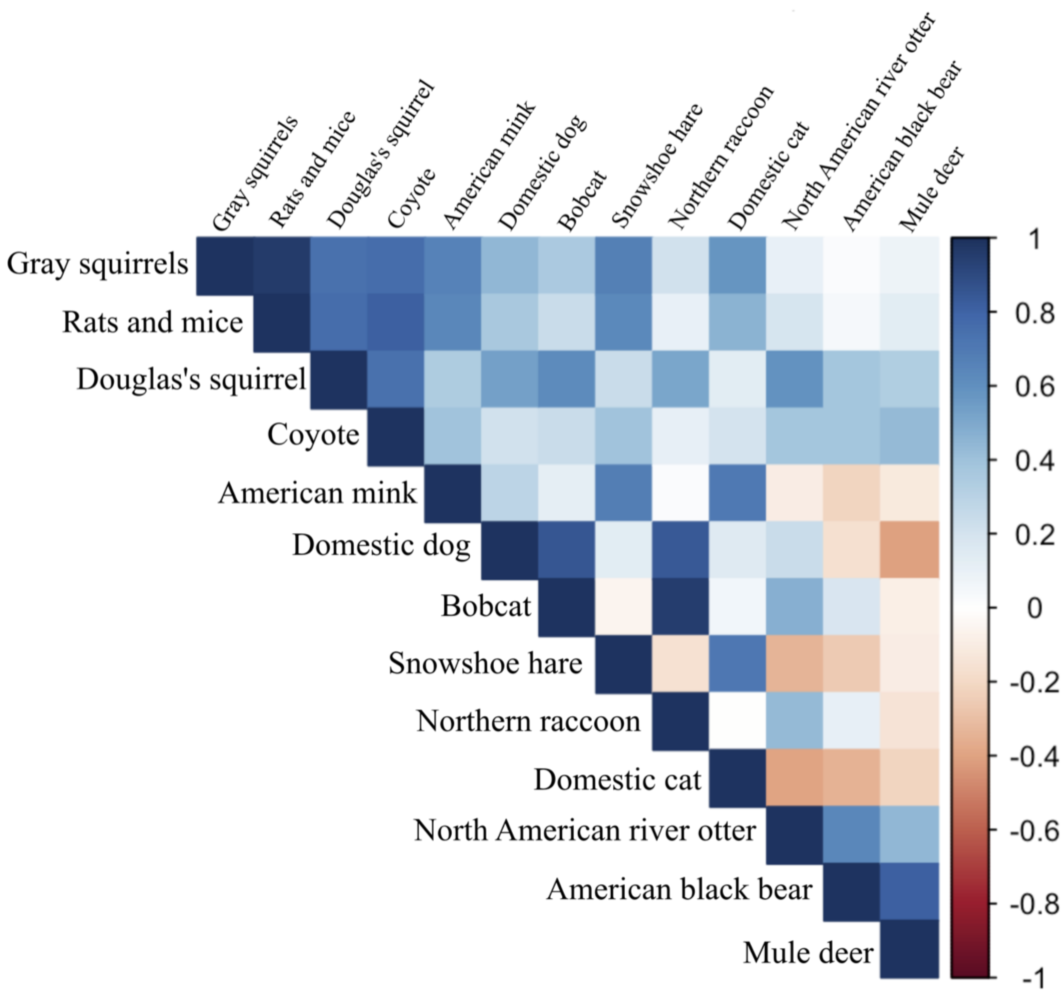


Figure D.2. Species co-occurrences among the mammalian community. This plot was generated at the site level (i.e., groupings of stream, riparian, and matrix cameras).