Grizzly Bear Habitat Connectivity in Southwestern British Columbia

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Southwest BC Grizzly Bear Study

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EXECUTIVE SUMMARY

The objective of this research is to identify areas of population connectivity between the South-Chilcotin, Squamish-Lillooet, Garibaldi-Pitt, and Stein Nahatlatch grizzly bear populations in southwestern British Columbia. These populations of conservation concern are at the southwestern extent of grizzly bear range in North America and have varying degrees of genetic, demographic, and geographic isolation between them. Fragmentation is a key threat to population recovery in the region and is the result of high levels of historic human-caused mortality and persecution in the valley bottoms that separate populations, contemporary mortality resulting from conflict with humans, and geographic features including large lakes, rugged mountains, and icefields. Connectivity increases the resilience of each population to demographic and environmental fluctuations and protects populations from loss of genetic diversity and the deleterious effects of inbreeding. Restoring historic connectivity and maintaining existing interpopulation connectivity is essential for the long-term persistence of grizzly bears in the region.

Based on 239,283 daytime locations from 57 bears wearing GPS collars across a 51,624 km^2 area, we used seasonal resource selection functions to identify core habitat areas in the region and to identify pathways of connectivity between them. We evaluated connectivity by identifying the natural and human-caused barriers preventing it and estimated the least-cost- paths among core habitat areas and across population fractures. Resistance to movement across the landscape was a function of inverse habitat quality and permanent human infrastructure density. We used this information to identify pinch points in connectivity by applying the principles of circuit theory to areas where movement is constrained by human or geographic factors. The resulting models identify areas where grizzly bear movement is constricted into pinch points where interpopulation connectivity is most likely because of geographic and human-caused barriers to connectivity.

Conserving the small and isolated Stein-Nahatlatch and the nearly extirpated Garibaldi-Pitt populations will require conservation efforts within the population as well as in the fractures that separate them from neighbouring recovering populations. As a result, the most important fractures to restore are the South Chilcotin—Stein-Nahatlatch fracture between Lil'wat/Mount Currie, and N'Quatqua/D'Arcy and the Squamish-Lillooet—Garibaldi-Pitt between Squamish and Pemberton. Maintaining connectivity and low mortality risk between the South Chilcotin and Squamish-Lillooet is important for regional population resilience and long-term population persistence.

Connectivity models can be applied to compare alternative conservation actions and used as a decision-making tool to guide the establishment of secure movement corridors for grizzly bears. Population connectivity at the pinch point scale across partial and complete population fractures can be compared and weighted using the resulting connectivity models. Connectivity models can also be applied to intrapopulation connectivity and assessing the impacts of potential developments for industry or recreation on the connectivity between extant core habitat areas.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Most of the world's large carnivore populations cover a fraction of their historic distribution and are declining. In addition to historic and sometimes contemporary intolerance for coexistence, rapidly growing human populations, expanding permanent settlements and agriculture, have resulted in the extirpation of many species from parts of their former ranges. Some large carnivore species are hunted for sport or animal parts (Weber and Rabinowitz, 1996), and many are killed by humans because they pose real, or perceived threats to personal safety and property such as livestock (Laliberte and Ripple, 2003; Mattson and Merrill, 2002). Population limitation from human persecution is density-independent — human density does not depend on carnivore density — therefore it frequently results in extirpation where humans and carnivores overlap

Over time these local extirpations culminate into a common geographic pattern of extinction that begins with the contraction of species' distributions into peninsulas and islands of occupancy. These are then sequentially extirpated over time (Henschel et al., 2014; Kenney et al., 2014; Proctor et al., 2012; van Oort et al., 2011) because following fragmentation, the smaller, isolated populations face an increased risk of extinction due to behavioural, genetic, or demographic Allee effects, and because of the declining ratio between the remaining suitable habitat and unfavourable conditions along the edge of their distribution (Frankham et al., 2019).

Stopping and potentially reversing population fragmentation and subsequent extirpation requires understanding the complex interaction between mortality risk and food availability that drive the realized population density on the landscape. Reconnecting populations, therefore, requires reversing the mechanisms that underpinned fragmentation in the first place, as well as ensuring there is sufficient high-quality habitat spatially connecting the separate populations.

Habitat quality and mortality risk can vary broadly across a species distribution. Patches of high-quality core habitat are often naturally separated by marginal or poor habitat. Habitat loss generally occurs when high-quality habitat is degraded or altered resulting in the reduction in overall habitat availability. Fragmentation occurs when habitat change or increased localized mortality results in the division of core habitats by marginal or unusable areas. Habitat fragmentation can affect the spatial and temporal patterns of habitat use by individuals and can vary among individuals sometimes affecting certain demographics more than others. In some cases, the division is severe enough to limit dispersal between populations and they become genetically separate, fractured populations.

Fractured populations decrease population resiliency and the ability to adapt whereas connected populations are more impervious to external pressures such as climate change or shifts in ecosystem composition than fragmented ones because they can receive new individuals that maintain the genetic diversity required to adapt to changing environments. On a shorter timescale, habitat connectivity allows individuals to move or disperse among areas to spatially shift habitat use to thrive in dynamic environments.

Linkage zones are smaller areas of usable habitat that connect much larger areas of core habitat. In fragmented landscapes, maintaining population connectivity via linkage zones will increase the likelihood of population persistence by allowing meta-population functions such as genetic and demographic rescue to portions of the population that are small and face additional threats to their persistence. Linkage zone attributes are species and ecosystem specific and provide secure areas that dispersing individuals are likely to incorporate as part of their home ranges.

Grizzly bear (*Ursus arctos*) distribution in North America is expansive, however the southern edge is contracted into two narrowing peninsulas of occupancy that both end in isolated populations of varying sizes (Mclellan, 1998; Proctor et al., 2012). The eastern peninsula extends along the Columbia and Rocky Mountains into Montana, USA. The western peninsula of occupancy extends along the Coast Mountain ranges of British Columbia, ending in five populations considered by the BC provincial government to be of extreme conservation concern (M1)(Environmental Reporting BC, 2020) . Population surveys in 2004-2007 obtained by large-scale DNA mark recapture methods that spanned the southwest region identified major geographic and genetic fractures as well as large differences in grizzly bear density among some of these populations (Apps et al., 2014, McLellan 2019). Fracture zones inhibit animal movement between populations, specifically, the Garibaldi-Pitt population had few (likely <10) individuals and may be functionally extirpated, and the Stein-Nahatlatch is considered “Critically Endangered” by the IUCN (McLellan et al., 2017). DNA mark recapture-based monitoring and monitoring GPS collared bears in three of the threatened populations showed the small and isolated Stein-Nahatlatch population continues to decline despite the cessation of legal hunting in 2000 (McLellan et al., 2021, 2019) while neighbouring South Chilcotin and Squamish-Lillooet are increasing (McLellan et al., 2021, 2019; Pers. Comm. S. Rochetta MFLNRORD).

The futures of the Stein-Nahatlatch and Garibaldi-Pitt grizzly bear populations are perilous (Figure 1). In addition to maintaining current core habitats and continuing to reduce human-caused mortality, the persistence of these populations will require long-term connectivity with the neighbouring Squamish-Lillooet and South Chilcotin populations. This is accomplished by building and maintaining linkage habitats between populations and promoting human-bear coexistence through conflict prevention measures. In fragmented landscapes, linkage areas are often pinch points in connectivity areas between core habitats, sometimes less than 2 km wide for grizzly bears (e.g. Proctor et al 2015), but are vital for inter-population connectivity by allowing for dispersing individuals to move across population boundaries, increasing gene flow and metapopulation function.

The objective of this research is to identify probable linkage zones across human-caused population fractures that separate five grizzly bear populations, of which four are considered “threatened”, at the southwestern extent of their North American range (Figure1). We first used resource selection models, derived from GPS grizzly bear locations, to predict core habitat areas and habitat quality across the landscape (Manly et al., 2002). We defined resistance to movement as the inverse of habitat quality plus reduced survival probability due to human settlement. We then estimated the cumulative cost-weighted-distance among core habitats where the movement cost was additive as a hypothetical bear moved from a core area toward another; if the resistance to movement was high, or the distance was far, then the associated cost weighted distance would be high. Within high-quality core habitats, there is little resistance to animal movement, it is not spatially constrained and animals move freely, but, in areas of higher resistance, such as near human settlement or in steep, rocky areas rarely used by bears, movement is constrained, funnelling possible movement pathways into spatially constricted areas. The likelihood that a bear will travel through these constricted linkage areas between habitat cores is mathematically analogous to current theory used to measure the electrical current through pathways with varying resistance (McRae et al., 2008). As a result, we can apply the principles and mathematics of circuit theory to predict habitat linkage areas and possible pinch-points in them between core areas and across population fractures (Washington Wildlife Habitat Connectivity Working Group, 2010). Using circuit theory to model this movement, current flow per unit area increases as it is concentrated between areas with high resistance.

The resulting habitat selection information, including identifying core habitats, population linkage areas, and pinch-points across human-caused population fractures, will provide target areas for conservation initiatives. Additionally, understanding habitat connectivity in more remote, wilderness areas improves the ability to assess potential impacts of rapidly growing recreational use of the backcountry or industrial development such as power projects, mining, and logging.

STUDY AREA

The 51,624 km^2 study area is located in the Coast Mountain Range north of Vancouver, B.C (Figure 1), with area overlapping parts of the Tsilhoot’in, Lil’wat, St’át’imc, Nlaka’pamux, In-SHUCK-ch, and Squamish Traditional Territories. The area is rugged, with elevations ranging from sea level to 3,237 m. Air masses moving eastward from the Pacific Ocean result in temperate rainforests dominated by cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) at lower elevations and either mountain hemlock (*Tsuga mertensiana*) or subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) higher on the mountains on the western edge. On the eastern, lee side of the mountain range, the climate becomes increasingly dryer and low elevation forests are dominated by interior Douglas fir (*Pseudotsuga menziesii*). In the transition between wet and dryer forests, there are patches of whitebark pine (*Pinus albicaulis*), a tree species of conservation concern, dominated subalpine parkland. The northern part of the study area extends into the Sub-Boreal Pine/Spruce forests dominated by lodgepole pine (*Pinus contorta*) interspersed with wetlands. The climate in this region is characterized by cold, dry winters and cool, dry summers and was recently heavily affected by wildfires, particularly in 2009 and 2017.

Grizzly Bear Population Geography

There are five grizzly bear population units in the study area with varying population density and growth rates (Figure 1; Table 1). The South Chilcotin population has approximately 225 bears and a moderate conservation ranking due to historic mortality. It is geographically and genetically connected to the Squamish-Lillooet, Toba-Bute, and Kilnaklini-Homathko populations (Province of British Columbia, 2012) with some individuals moving across population boundaries. Genetic population monitoring in the southern part of this unit indicated that the population is growing following the cessation of hunting in 2000 (McLellan et al., 2019). The adjacent Toba-Bute population has low conservation concern due to its stable size, connectivity, and relative lack of negative human effects. It is also connected with the Knight-Bute population to the north and the Squamish-Lillooet population to the southeast.

Table 1: Grizzly bear populations at the southwestern extent of their range. North Cascade population unit is excluded from this analysis but has fewer than 6 animals and is likely functionally extirpated.

Population	Size	Trend	Connected
South Chilcotin	222	Growing	Yes
Toba-Bute	130	Growing	Yes
Squamish-Lillooet	46	Growing	Yes
Stein-Nahatlatch	22	Declining	Limited
Garibaldi-Pitt	<10	Declining	Limited

The Squamish-Lillooet grizzly population is likely growing but it is still considered high conservation concern by the province because of high levels of human activity and habitat encroachment. At least one bear from this population has temporarily crossed into the Garibaldi-Pitt population unit, however, her home range remains primarily in the Squamish-Lillooet. Genetic capture program in the Garibaldi-Pitt unit did not identify any resident grizzly bears however observations of bears feeding on Salmon from the Pitt River and tributaries including a female with a yearling in 2019 (pers. comm. S. Rochetta, MFLNRORD) indicate the potential of a small resident population (<10 individuals). As a result, there is extreme conservation concern for this area and maintaining connectivity to neighbouring populations is critical.

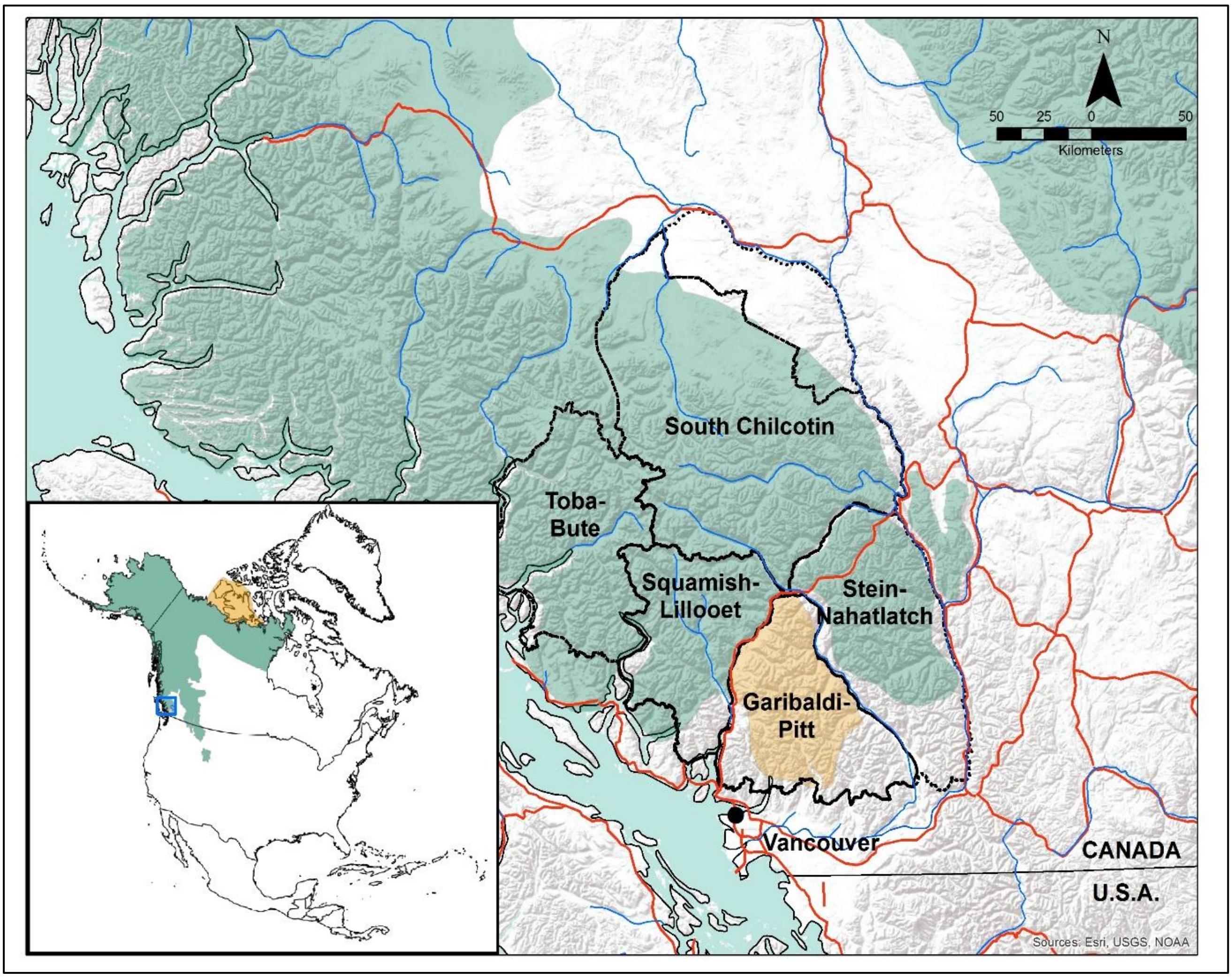

Figure 1: Extant (green) and vagrant (yellow) grizzly bear distribution in North America (inset) and southwest British Columbia, Canada. The grizzly bear population unit boundaries (black dash) for the population units considered in this analysis: South Chilcotin, Toba-Bute, Squamish-Lillooet, Stein-Nahatlatch and Garibaldi - Pitt. Highways (red lines), major rivers (blue lines), international border (bottom thin solid black line).

The Stein-Nahatlatch population is considered critically endangered by IUCN conservation standards and critical by the Province because it has fewer than 25 grizzly bears and, despite the cessation of hunting in 2000, is likely declining (McLellan et al., 2019). Few males have immigrated into the population and no resident females have moved between populations or across highway 99 that bisects the population unit near Duffey Lake. It is likely that this population has been isolated for many generations and is suffering from small population effects such as reduced fitness from inbreeding and increased impacts of demographic stochasticity (McLellan et al., 2021).

Conservation of these most southern populations is also critical for the potential recovery of the North Cascades grizzly population (not shown on map) that spans the United States – Canada border in the Cascade Mountains. There have been recent sightings of grizzly bears in this population unit, but it is unlikely that the population is over 5 individuals.

Grizzly Bear Food Sources

Grizzly bear habitat use and food sources vary substantially across the study area. Due to high snowfall and rugged mountains, avalanche chutes are common throughout the mountainous parts of the area and are rich in glacier lilies (*Erythronium grandiflorum*), Canada thistle (*Cirsium edule*), cow parsnip (*Heracleum lanatum*), and other foods preferred by grizzlies in the spring. In flatter parts of the area, spring and summer forage is often near stream banks and in open, nutrient-rich habitats and wide flat floodplains. Species commonly consumed in these habitats include cow parsnip, horsetails (*Equisetum spp*.), dandelions (*Taraxacum officinale*), and other herbaceous plants.

In the late-summer and early autumn grizzly bears often forage on black huckleberry (*Vaccinium membranaceum*) or Cascade blueberry (*V. deliciosum*) in the western, wetter portions of the area. Toward the eastern part of the area, in the rain shadow of the Coast Mountains, grizzlies forage on whitebark pine cones from trees or by excavating squirrel middens (Iredale et al., 2016; McLellan and McLellan, 2015; Senger et al., 2007). Other fruit commonly eaten in the drier parts of the area include Saskatoon berries (*Amelanchier alnifolia*), Buffalo berry (*Shepherdia canadensis*), and pin and choke cherries (*Prunus pensylvanica* and *P. virginiana*). Throughout the study area grizzlies sometimes ate black bears (*Ursus americanus*), moose (*Alces alces*), mule deer (*Odocoileus hemionus*), mountain goats (*Oreamnos americanus*), marmots (*Marmota caligata*), and meadow voles (*Mycrotis pennsylvanicus*).

Despite the availability of salmon species in rivers and streams in all five grizzly populations, salmon foraging is only common in the Squamish Lillooet population and the western part of the South Chilcotin population and not all individuals forage on salmon in any area. Few bears forage on salmon in the Stein-Nahatlatch population and this behaviour is limited to the Nahatlatch area.

Many herbaceous bear foods are also important to local First Nation communities including Stáqwem (*A. alnifolia*), Xúsum (*S. canadensis*) and úsa7 (*V. membranaceum*) (Senger, 2012)

Human Geography

Approximately 45,000 people live in the study area with most in Squamish (~21,000), Whistler (~13,000), Pemberton (~3,000), and Lillooet (~2,500). Except for the Toba-Bute population unit, there is some human settlement along the intersecting population unit boundaries. Highway 99 and the communities of Brakendale, Whistler, Pemberton, and Lil’wat/Mount Currie form the boundary between the Squamish-Lillooet and the Garibaldi Pitt Grizzly populations. West of Pemberton, the Lillooet River valley is broad and has been mostly converted into agricultural land. There are many hobby farms (5-10 acres) and large commercial produce farms. Surrounding the communities there is a substantial network of recreation trails for biking, hiking, and horseback riding.

The Squamish River runs in the centre of the Squamish-Lillooet population unit and has some human settlement, mostly at its southern end. Due to its proximity to Vancouver and neighbouring cities (>2.1 million people), this area receives a high volume of recreation traffic throughout the year. Thousands of people visit the Squamish Valley for camping and other activities. Further east, the resort municipality of Whistler receives approximately 1.65 million visitors in the summer months, many accessing regional trails and outdoor activities.

The Garibaldi-Pitt population unit east of Whistler also receives a high volume of human recreation traffic. Each year over 110,000 day-users and 30,000 overnight visitors will visit Garibaldi Park. On the east side of the Pitt River, the population is separated from the Stein-Nahatlatch population by Harrison Lake, Lillooet Lake, and the small communities of Port Douglas, Skookumchuck, and Tipella. The southern end of the unit borders on the Fraser Valley including the cities of Coquitlam, Langley, Abbotsford, Chilliwack, and Agassiz. Due to high human population density and agriculture, this area is not suitable for grizzly bear recovery or connectivity.

The Stein-Nahatlatch is separated from the South Chilcotin by several communities along Pemberton-Portage road from Lil'Wat/Mount Currie to N'Quatqua/D'Arcy and by Seton and Tsal'alh villages which covers most of the 2 km of land between Seton and Anderson Lakes. Together the lakes are approximately 45 km long and 1.5 km wide. The Stein-Nahatlatch population is also bisected by highway 99 from Lillooet Lake to the town of Lillooet near the confluence of the Cayoosh and Fraser rivers. This area is not settled by humans and collared male bears cross regularly. The Stein Valley Nlaka'pamux Heritage Park is a large (1,300 km^2), un-roaded protected area at the centre of the population unit. There are several recreation properties at the lower end of the Nahatlatch valley and many communities along the Fraser River to the east of the population.

The South Chilcotin population unit is bound by the Fraser River to the east and Highway 20 to the north. There are several small communities including, Xeni Gwet-in and Yunesit'in, on the periphery of the population unit as well as recreation homes along Chilko and Taseko Lakes. Near the southern end, there are several recreational and permanent resident properties around Gun and Tyaughton Lakes which are also popular staging areas for accessing the many recreation trails in South Chilcotin Mountains Provincial Park. These trails are internationally renowned and are popular with mountain bikers, horseback riders, and hikers. A paved highway parallels the Carpenter Reservoir from the Bridge River to Goldbridge while a gravel forest service road parallels the Hurley River and drops down to the upper Lillooet River and Pemberton and is open only in summer months. This road is crossed regularly by both female and male bears. Vehicle traffic throughout the study area has increased substantially in the last decade.

METHODS

Capture and Collaring

The information used in this analysis was from three research projects, however, grizzly bear capture and collaring protocols used similar techniques and personnel overlapped among efforts. The first grizzly bear capturing program in the South Coast mountains began in the northern part of the Stein-Nahatlatch grizzly bear population unit in 2005 and was expanded into the McGillvary Mountains of the South Chilcotin GBPU the following year (Table 2). Capture efforts in the Stein-Nahatlatch ran from 2005 to 2013 when it became apparent that the population had unusually high mortality and, although no bears died or were injured as a result of capture in any of the three studies, we felt any risk was too great to continue the capture program in that population. We continued to monitor the collared bears there until the last collar dropped in 2018. In 2008, a separate program was initiated in the Squamish-Lillooet population unit and expanded into the southwestern part of the South Chilcotin GBPU. Capture in these areas continued until 2018 and overlapped with the McGillvary Mountains study with collared bears being monitored through 2020. In 2014-2015 grizzly bears were captured and monitored in the South Chilcotin GBPU north of Carpenter and Downton Reservoirs (Iredale, 2016).

Except for a few bears which were captured using foot snares, grizzlies were immobilized from a helicopter using a combination of tiletamine and zolazepam (Telazol®) administered with a projectile. McLellan and McLellan (2015) provide a detailed description of capture procedures. Capture protocols were approved by the Province of British Columbia. Before 2010 bears were fit with Lotek collars (Argos 2005; 4400s and 4400m) programmed to obtain either 8 or 24 locations per day. From May to November bears were located bi-monthly by aircraft and the locations were downloaded. After 2010, collars had GPS uplink to advanced telemetry systems iridium satellites, and locations were immediately available for download, fix rates were one, 12, or 24 per day. Collared bears were monitored until their collar batteries died, the collar dropped, or the bear died. All collars had a mortality sensor that would indicate if the collar had stopped moving for over 24hours. Mortality signals were investigated to recover the collar, or in the event of mortality, to perform a necropsy and determine the cause of death. All collars were fit with a canvass spacer that rotted off so that the collar was guaranteed to fall off even if it malfunctioned.

Table 2: Sampling effort and the timeline for data collection by grizzly bear population unit in the Coast Mountains of southwestern British Columbia.

Population Unit	**Data Years**	**Males**	**Females**	**Total**
Squamish-Lillooet *	2008-2020	11	15	26
South Chilcotin (North of Carpenter Lake)	2014-2018	3	10	13
South-Chilcotin (South of Carpenter Lake) *	2006-2017	10	21	31
Stein-Nahatlatch (North of Stein River)	2005-2013	9	8	17
Total	2005-2020	33	54	87

* In this table bears that moved between population units are assigned to the population where they were initially captured

Linkage model parameters

Modelling linkage across partial or complete human-caused population fractures is a multi-step process. The first step is identifying common seasonal transition patterns in the ecology and behaviour of grizzly bears and then deciding which seasons and behaviours are most appropriate for modelling habitat selection where population fractures occur. Combining data from multiple seasons or behaviours into one selection model will introduce considerable variation and reduce both accuracy and precision in estimates of selection patterns. For this analysis, we target habitats selected by grizzly bears for feeding and moving in low elevation, valley bottoms where all the human-caused fractures occur. To further improve the accuracy and precision in estimates of habitat selection by grizzly bears for habitats used while they are active, we excluded bear locations obtained between evening and morning civil twilight when bears are most often sleeping from model building (McLellan and McLellan, 2015).

Foraging and movement behaviours vary among seasons. Grizzly bears, and especially males, tend to have broader movements in the springtime when they are in search of mates. Later in the year, when they shift into hyperphagic feeding behaviour, their movements become more restricted and wide-ranging movements are less common. It is also more common for bears to select low elevation habitats, that are sometimes near human settlements, in the spring than in other seasons because these areas green-up earliest. Also, the foods and foraging behaviour are more consistent across the entire study area during spring than at other times of the year therefore habitat selection estimates will be more precise and accurately predict selection than for seasons with more individual variation in behaviours. All bears monitored in these projects foraged on shoots, grasses, and new vegetative growth in the spring whereas later in the summer and autumn foods varied more widely. For these reasons, we targeted habitat selection during spring and early summer months for predicting linkage areas.

Although spring habitat may be most appropriate for defining low elevation habitat selection and general movement, the most important habitat types for sustaining population density and defining grizzly bear home ranges are the late summer and early autumn habitats (McLellan 2015, McLellan 2020). Bears are hyperphagic at this time of year, focusing almost exclusively on foraging and consume most of their annual caloric intake needed for reproduction and sustaining them through winter hibernation. Patches of high-energy foods such as huckleberries or whitebark pine often define the edge of a home range and are the destination to which a bear will travel for food. To include these important habitat areas in our linkage model, we use an autumn specific RSF to predict core habitat areas. Together with the spring model core areas, these form the nodes between which movement is predicted, including those across human-caused population fractures.

In this study area there some months where the individual variation in habitat selection is high. For example, in July, many bears will feed on Saskatoon berries in some parts of the study area while others will remain focused on roots and vegetation (McLellan and McLellan, 2015). Similarly, many females will stop foraging altogether and begin denning in mid-October, while other bears will continue to forage on berries, Whitebark pine cones, or salmon throughout the month and into November. Seasonal habitat selection was assessed for spring (May-June) and late-summer/ early autumn (August-September) when foraging behaviours are usually consistent for individuals(Iredale, 2016; M. L. McLellan and McLellan, 2015).

Resource Selection Functions

To predict habitat selection across the landscape and delineate core habitat areas, we developed mixed-effects resource selection functions (RSFs) for the spring and autumn seasons. RSFs are a well-described modelling technique used to assess whether the probability of an animal using a specific resource is proportional to the availability of that resource (Manly et al., 2002). We considered habitats available to each bear by those within their annual 95% minimum convex polygon (MCP) home range and we only included individuals that had been collared for a complete year or more. The number of locations needed to accurately estimate habitat availability is specific to the combination and degree of autocorrelation of the habitat variables used in an analysis, the heterogeneity of the variables on a landscape, and the size of the area for which we want to estimate availability (Northrup et al., 2013). We found that matching the number of random locations to used locations was sufficient to capture the variance of each parameter and accurately estimate availability.

Model building followed the methods described in Proctor et al. (2015). First, we conducted a univariate logistic regression to estimate the explanatory power of each variable using McFadden's pseudo-R^2 statistic. Predictor variables were tested for multicollinearity which can decrease the precision of the model and possibly create erroneous results (Graham, 2003); if two predictor variables had a Pearson correlation coefficient of >0.6 (Nielsen et al., 2009) we retained the covariate with the highest explanatory power. Multivariate mixed-effects logistic regressions were built by adding each variable from high to low in order of their individual pseudo-R^2 value including project and individual bear as a random effect. If the inclusion of a variable increased model performance by >5% or its exclusion changed the β parameter by more than 20%, it was retained in the final model (Bursac et al., 2008). Any removed parameters were then re-added in reverse order to ensure that the order did not confound the results. Model building was carried out in program R V.4.0.2 (R Core Team, 2021) using lme4 V.1.1-26 (Bates and Mächler, 2016), pscl V.1.5.5 (Jackman et al., 2020), and MASS 7.3-53.1 packages (Venables et al., 2021).

Model performance was tested for the fixed effects components of the model using repeated k-fold cross-validation (Boyce et al., 2002). Bear use data were partitioned into k=5 groups and, in sequence, each fold of 20% was withheld for model testing while the remaining 4 groups were used to iteratively train RSF model. The available data RSF scores were estimated and partitioned into 10 quantile bins. The RSF scores were estimated for the 20% withheld use data and 20% of the random data were partitioned into the quantile bins. Spearman's rank correlation coefficient was estimated for the frequency of the cross-validation use locations and bin rank. The entire process was repeated 1000 times. K-fold estimate function was developed in R.

Environmental Variables

Environmental covariates used to develop habitat models fall into seven categories including landscape cover, terrain variables, whitebark pine cover, canopy closure, disturbance history (fire and harvest), abiotic ecological factors, and open road density (Table A1-1, Appendix 1). We defined landscape cover to be one of 15 discrete functional habitat units believed to be identifiable by both bears and humans and likely differentially selected by grizzly bears. Polygon boundaries were based on boundaries delineated in the vegetation composite polygon spatial layer (VRI) created by the ministry of forests (Ministry of Forests, 2019). Each polygon was classified first using the British Columbia Land Cover Classification Scheme levels 1 through 5 to delineate among rock, ice, water, wetland, grassland, forested, herbaceous, and heather-dominated habitats. Forests were classified into dominant forest types according to biogeoclimatic zones described by the dominant tree species of mature forests (MacKenzie, 2012).

Non-forested areas were divided into vegetated and non-vegetated. In the alpine, the base map boundaries were often incorrect, so non-vegetated areas were re-classified as vegetated if they had a greenness level of 5 or more on a scale of 1-10 where 1 is not green, or certainly rock/ice. The reclassification scale was developed by examining the relative greenness in areas that had been visited by researchers and where vegetation plots had been recorded. To distinguish between avalanche chutes and alpine areas we used the provincial BEC layer to separate unforested areas classified in the VRI into above treeline, or alpine, and below treeline unforested layer (MFLNRORD, 2019a).

Avalanche chutes were defined as habitats kept in a perpetual sub-seral state by frequent disturbance caused by sliding snow. Each avalanche chute was manually edited by overlaying with the ortho photo and drawing the boundaries to delineate different sub-types or partition the chute into different avalanche chute types including herbaceous, krummholz, rock, and shrub-dominated avalanche chutes. Above alpine habitats were classified as herb dominated, heather dominated, rock and ice. Polygons dominated by human use such as homes, farms, schools, and towns were defined as anthropogenic. The percent of whitebark pine cover and overall canopy cover in a polygon were each included as additional continuous variables.

Disturbance history was classified as harvest or wildfire. The age of disturbance was defined as the difference between the year of disturbance and the date of the location. Random locations were assigned a year value matched to a bear location date. Histograms of bear use in disturbed sites were used to define disturbance age categories that explain the most variation in selection and availability.

Several terrain variables shown in other research to be useful indicators of grizzly bear habitat were included (Apps et al., 2004; Ciarniello et al., 2007; Johnson et al., 2006; Proctor et al., 2015) . A digital elevation model with 30 X 30 m resolution; (ESRI, 2020; GEO BC, 2011) was used to derive elevation, slope, aspect, solar radiation, compound topographic index (CTI) as a surrogate for terrain wetness (Rho, 2002), and terrain ruggedness index (Evans, 2004). Aspect values were then used to calculate southerliness and westerliness each ranging from 0 to 1 where 0 is North or East respectively and 1 is south and west respectively. Enhanced vegetation index (EVI) is an index of vegetative productivity, derived using average values from Landsat 8 satellite between 2013- 2018 and δ EVI which subtracts summer greenness from fall greenness to reflect changing deciduous species, whereas coniferous species should be similarly green between seasons (Chander and Markham, 2009).

By far most grizzly bears over two years of age end up being killed by people and these are almost always killed within shooting distance (200 m) of a road (McLellan, 2015) and road density has been linked to grizzly bear habitat selection and density at various scales (Proctor et al., 2019). Open road density was included as a measure of the linear road distance per square kilometre. Roads layers were obtained by amalgamating digital road layers from the provincial database, Ainsworth Forest Company, and manually digitizing new roads not yet on these databases. Overgrown or reclaimed roads that were no longer travelable by vehicle were removed.

Seasonal Habitat Selection and Core Habitats

The resource selection function was used to produce predictive maps of the relative probability of occurrence across the study area (Boyce and McDonald, 1999; Manly et al., 2002). Each seasonal RSF model was delineated by bear population unit and reclassified into 1000 equal-area quantile bins to account for unequal distribution of habitat quality between population units and reduce the influence of outliers. Bear locations were overlayed with projected RSFs to determine at what RSF score the odds of selection exceeded one. RSF scores were aggregated by blocks of 10 and retained if a mean above the selection threshold. Habitat blocks within 500 m of other blocks were amalgamated and those exceeding > 0.6 km^2, which is the radius of the average daily home range size of female grizzlies in this study area, were defined as core habitat areas. Areas within 500m of a highway or a human-occupied landscape were excluded as possible core habitats.

Human Resistance Layers

The density of buildings was used as a surrogate for mortality risk because humans are by far the most common cause of adult grizzly mortality in most populations, especially for those that overlap with rural residential and agricultural areas (Garshelis et al., 2005; Mace et al., 2012; B. N. McLellan and McLellan, 2015). Buildings were identified from the TRIM Enhanced Base map published by the MOFLNRORD and converted to point location for each (MFLNRORD, 2019b). Using a moving circular window with a radius of 500 m to estimate the building density surrounding each cell (Proctor et al., 2015). Resistance due to increased mortality risk was scaled from 0 to 1 where 0 is resistance such as within a core habitat area and approaches 1 in areas with high building density.

Linkage analysis and Connectivity Mapping

We calculated the cumulative least-cost-pathways of movement among core habitat areas based on both habitat quality and human-caused resistance to movement and survival. First, we calculated the cumulative cost-weighted-distance to a hypothetical bear moving across each 30x30 m cell away from a core habitat—the higher the resistance or the farther the distance the higher the cost. In this analysis, the resistance to traveling through each cell is the equally weighted combination of the scaled inverse spring RSF value for that cell and the scaled building density around the cell centre. The core specific cost-weighted-distance layers are then mosaicked together so that the least-cost-corridors between all the core areas in the study area are identified. The least-cost-corridors are the most likely pathway that would be taken by individuals that know the landscape rather than dispersing individuals exploring new, unknown areas because they are based on perfect knowledge of the landscape. Intact landscapes will have broad areas with low-cost distance values signifying that movement within those areas has little restriction. Barriers to connectivity will be highlighted by a few narrow pathways following one of the least-cost corridors.

Pinch points in connectivity are identified and mapped by applying the principles of circuit theory to produce current maps from the cumulative least-cost corridors. Using this method, probable bear movements are mathematically analogous to current density at each cell resulting from the current from the core areas and resistance in that cell (McRae et al., 2008). In broad areas with little resistance, the availability of multiple pathways increases so the current density across the area decreases. But if the same area connects multiple core areas, then the current density increases. Areas with high current densities can be pinch points for movement when other options for connecting two core habitats are limited. Predicted bear movements based on circuit theory are more likely to mimic dispersing individuals across an unfamiliar landscape because they model higher passage probabilities for random dispersers with few alternative pathways (McRae et al., 2008).

Linkage analyses were conducted using the Linkage Mapper® tool (McRae and Kavanagh, 2011) in ArcCatalogue V.10.8. and to run Circuitscape (McRae, 2012). We limited pathways to 50 km Euclidean distance which is less than the distance across an adult male home range but will include core areas on each side of the fractures.

RESULTS AND DISCUSSION

Grizzly Bear Locations

Between 2005 and 2020 we obtained 239,283 daytime locations from 57 grizzly bears (45 females;12 males) that were monitored for a year or more (Table 3). Of these 48 (81%) had more than 90% of their home range in one population unit. The remaining 9 (3 females 6 males) bears monitored for more than a year had home ranges that overlapped multiple population units (Table 3 Figures 2, 3).

Table 3: Grizzly bear population membership of collared bears from the South Chilcotin (SC), Squamish-Lillooet (SL), Stein-Nahatlatch (SN), and Toba-Bute (TB) populations in southwestern British Columbia. There was no capture effort in the TB population unit.

Population Units	Female	Male	Total
SC	26	2	28
SL*	10	1	11
SN	6	4	10
SC-SL	2	3	5
SC-SN		1	1
SC-TB		1	1
SC-SL-TB	1		1

*This includes one female that did cross from the SL into the GP but <10 % of locations were in the GP

Resource Selection Functions

The top spring RSF model included a positive relationship with EVI (greenness), solar radiation, west-facing aspects, slope, Whitebark pine cover, and a negative relationship with degree days below18 °C, winter precipitation as snow, and canopy cover. Areas that burned within 15 years were selected more often than older burns or unburnt areas and harvest age was relatively inconsequential (Table A1-2, Appendix 1). Terrain ruggedness, south-facing slopes, and all climate variables except those with degree days below18 °C, and winter precipitation as snow, were excluded in the first step of model selection because they were highly correlated with other covariates but had lower pseudo-R^2 and higher AIC. Both compound topographic index (index of wetness) and open road density were not significant predictors of bear use and did not improve model performance or affect coefficients of other predictor variables and therefore were excluded.

The top late summer RSF model included a positive relationship with δEVI, solar radiation, slope, and Whitebark pine cover, and winter precipitation as snow and a negative relationship with degree-days below 0 °C, and canopy cover (Table A1-3, Appendix 1). Burns were preferred over previously unburned areas or burns over 80 years old and those between 15 and 50 years old were selected over those between 50 and 80 years old (Figure 2). Logged areas between 15 and 30 years old were also preferred over more recent logging however selection over unlogged areas was not apparent after 30 years (Figure 2). Alpine herbaceous areas were selected over other landscape types followed by areas in mountain hemlock forests, possibly harvested or burned. Terrain ruggedness, southerliness, and all other climate variables were excluded in the first step of model selection because they were highly correlated with other covariates but had lower pseudo-R^2 and higher AIC. Wetness (CTI), aspect, and open road density were not significant predictors of bear use and did not improve model performance or affect coefficients of other predictor variables and therefore were excluded.

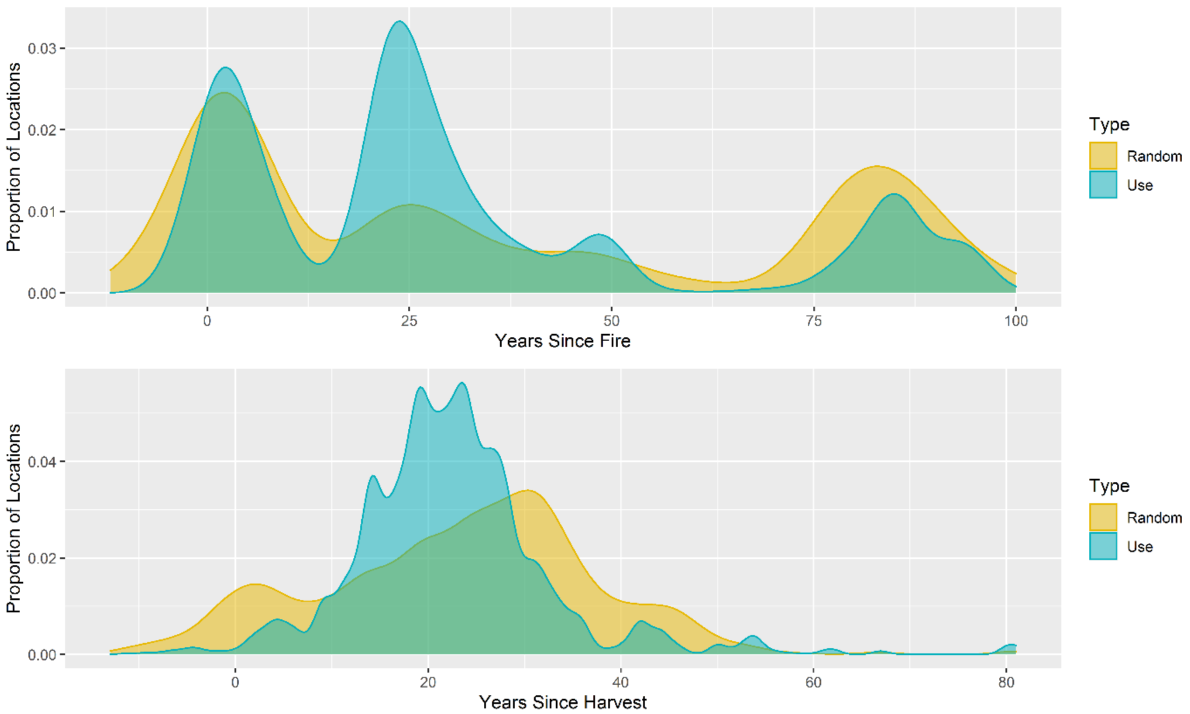

Figure 2: Proportion of use and available (random) locations by time since disturbance for fires and harvest across all seasons. Areas where the density of "use" exceeds "random" indicate selection. Locations at ages less than 0 are when the bear, or temporally associated random point, was before the area was disturbed; for age classifications for RSF models, these were considered undisturbed.

The average Spearman's rank correlation coefficient for each repeated k-fold cross validation between predicted and area-adjusted bins for RSF score was r_s=0.991 (95%CI 0.986 – 0.998) for the spring model and r_s=0.990 (95%CI 0.983 – 0.996) for the autumn model suggesting the models accurately predicted new data. The area under the ROC curve was 0.896 and 0.869 for the spring and late summer RSFs respectively indicating that even when some of the random locations were likely also used by bears, and therefore biasing the estimate low, the model had 90% and 87% predictive accuracy.

Core Areas

The ratio of selected habitat to availability indicated that bears' selection occurred for habitat in area-adjusted RSF rank bins between 62 and 68 for both spring and late summer RSF models and 50% of all bear locations were in bins above 78 and 80 (Figure 3). This resulted in 181 core areas across the study area. Of these, four were removed because they overlapped a highway or were within a 500m buffer around a human residence or other building which precluded them from being considered core habitat area. A large core area was removed from the Toba Valley bottom due to permanent camp infrastructure although it is still used by bears in that area. Though this area is likely important for those bears, it would not contribute to the estimated linkage zones and was left out due to its location on the periphery of the study area. An additional 27 core areas within a 500 m buffer of another were amalgamated resulting in 150 core habitats (Figure 4). The total area of core habitat ranged from 2%-6% of the total population unit area: 130 km^2 in the Toba-Bute, 529 km^2 in the South Chilcotin, 210 km^2 in the Garibaldi-Pitt, 378 km^2 in the Stein Nahatlatch and 339 km^2 in the Squamish Lillooet population units.

Home Range Distribution and Interpopulation Movement

Grizzly bear location data indicate five partial or complete population fractures in the study area (Figures 5-7). Despite consistent capture effort, collared female grizzlies did not use the area between Highway 99 (SN female-only fracture) and Pemberton Portage Road (SC-SN fracture; Figures 5 and 7). No female bears were identified in this area during 8 years of genetic monitoring using baited hair traps and rub sites (McLellan 2021, McLellan 2019). However, three collared adult male bears, all with Stein-Nahatlatch genetic origin, used this area (Figures 6 and 7). One of these was an older male captured and collared in the South Chilcotin that accessed fish in the Birkenhead River but, while monitored, did not move further south into the SN unit than the river channel and a nearby garbage dump on the edge of the SN. One sub-adult male frequently crossed the Highway 99 fracture while collared and has since been genetically tagged in the South Chilcotin population unit (McLellan et al., 2019). The third male frequently crossed the Highway 99 fracture while he was collared but not the SC-SN fracture along Pemberton Portage Road. He was never genetically tagged outside of the

Stein-Nahatlatch, nor did he have any genetically tagged offspring in another population (Apps et al., 2014; McLellan et al., 2019).

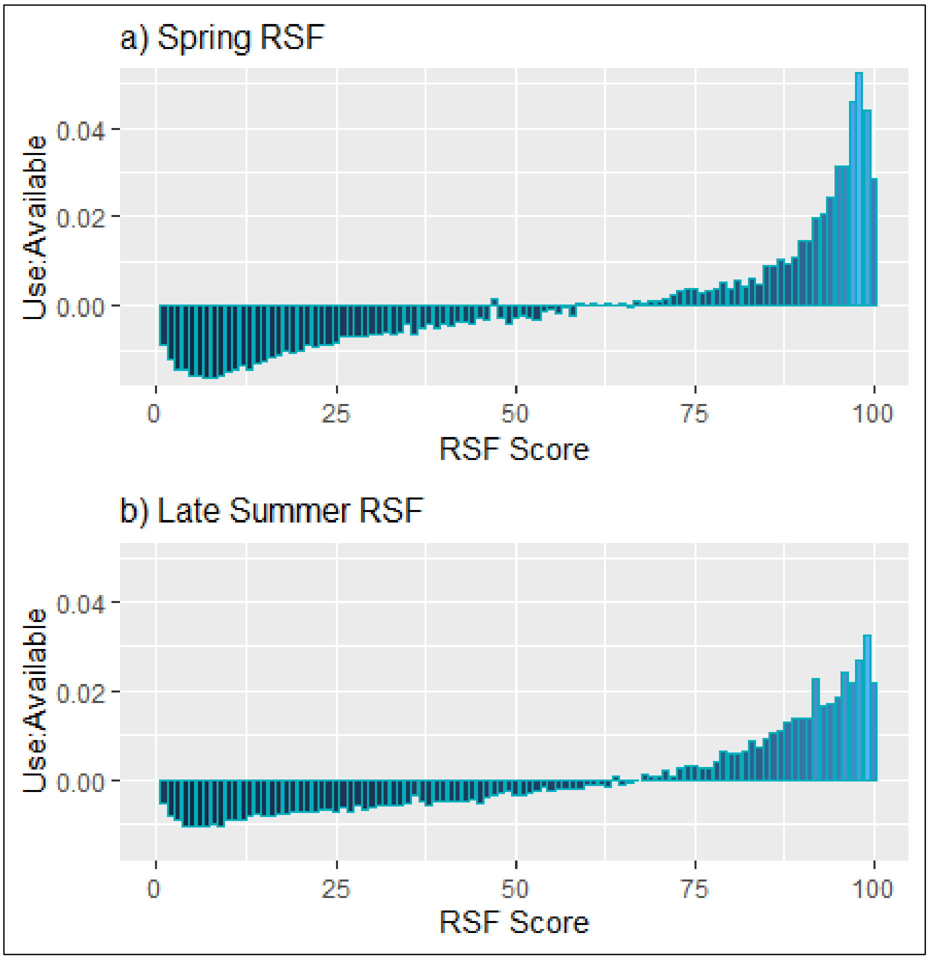

Figure 3:Ratio of the relative proportion of use and available (random) locations in each quantile bin. Each random bin has 1% of the area. Over half the use locations were in the top twenty bins for each model.

Seven females and eight males collared had some interpopulation movement between the South Chilcotin and the Squamish Lillooet populations. Of these, four males and three females accessed habitat within 500m of the Pemberton Meadows agricultural areas (Figure 5 and 7) and for the females this area was at the edge of their home range; none crossed the valley and returned more than once. The Pemberton Meadows was the north or south boundary of the home range of 9 other collared bears. Two males collared for less than a year used the Pemberton Meadows area and crossed this fracture repeatedly (Figures 6 and 7).

In an unusually remarkable event, an old adult female from the Squamish-Lillooet unit crossed into the Garibaldi Pitt unit through the town of Whistler and spent Oct 1st to November 14th, 2011 circumnavigating most of the GP unit before returning to the SL unit to hibernate. During this time, she travelled a minimum of 284 km, covering an area 3.5 times her previous annual home range. She also spent two 7-day and one 3-day bout not moving at all. At least one male, in 2011 and one female with a cub in 2019 were observed using the Garibaldi-Pitt population unit but none were genetically tagged in previous research (S. Rochetta MFLNRORD, pers comm).

Home range distributions and movements within the South Chilcotin population reflected capture effort and population fractures. Of the 12 female grizzly bears captured in the McGillvary Mountains area of the South Chilcotin population (between Downton/Carpenter reservoirs and SC-SN fracture), only one young female (6yrs old) had locations north of the Downton reservoir. This bear swam across the Downton reservoir (~800 m), suggesting that it was not a barrier to movement. She did not move between the two reservoirs near the town of Gold Bridge; however, this route was often selected by a collared male bear who was later shot by the Conservation Officer Services due to extreme food conditioning and habituation. Two other collared adult males have home ranges that did not cross the reservoirs. Genetic evidence suggests some historical separation of the McGillvary mountain portion from the rest of the South Chilcotin population (Apps et al 2014).

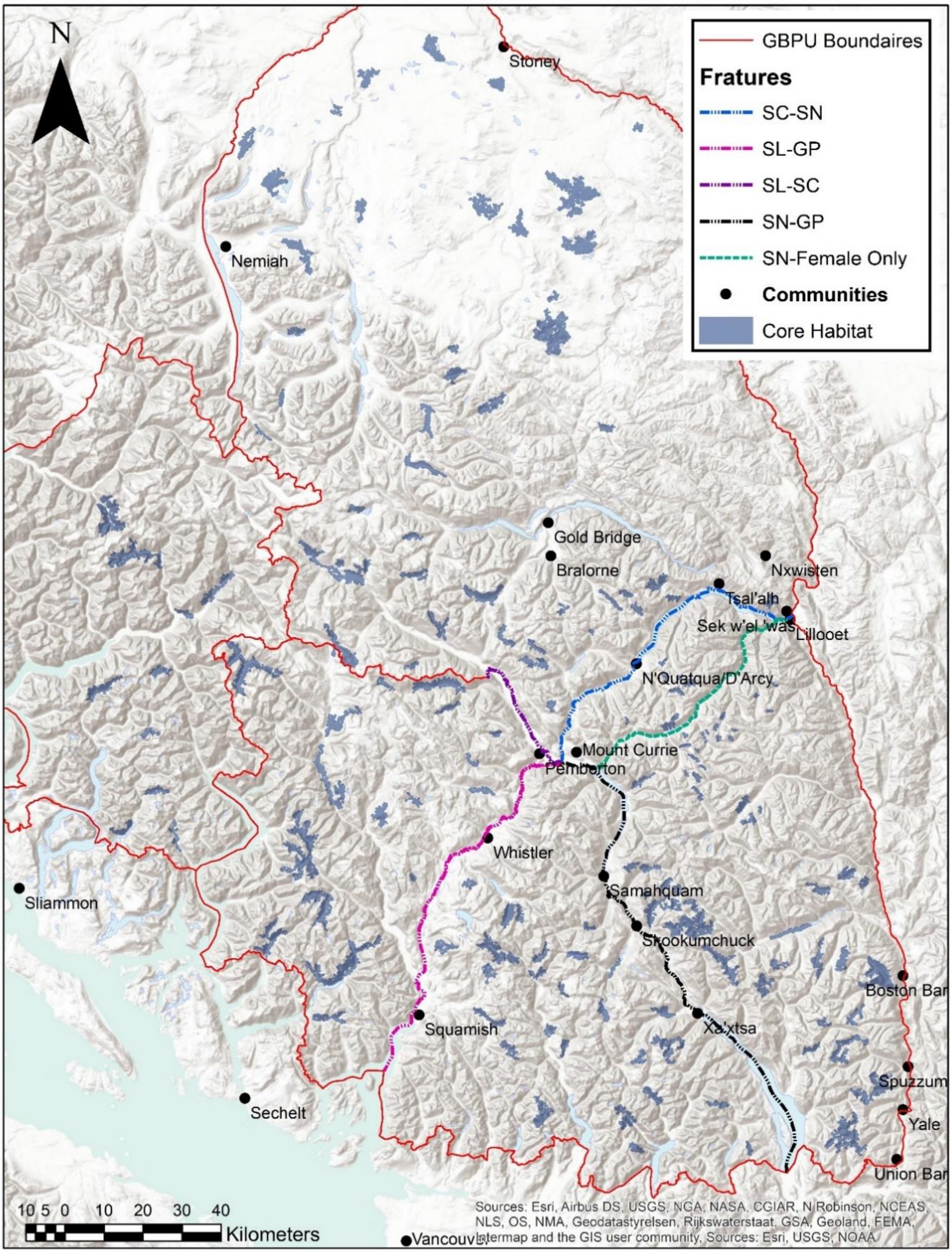

Figure 4: Core habitat areas identified from resource selection models for two seasons: spring (May-June) and late summer (Aug-September). Fractures along population boundaries include the South Chilcotin – Stein Nahatlatch (SC-SN), Squamish-Lillooet – Garibaldi-Pitt (SL-GP), Squamish-Lillooet – South Chilcotin (SL-SC) which is only along a portion of the population unit boundary, and the Stein-Nahatlatch – Garibaldi-Pitt (SN-GP). Within the Stein-Nahatlatch population, there is an additional female-only fracture along Highway 99 (SN-female only).

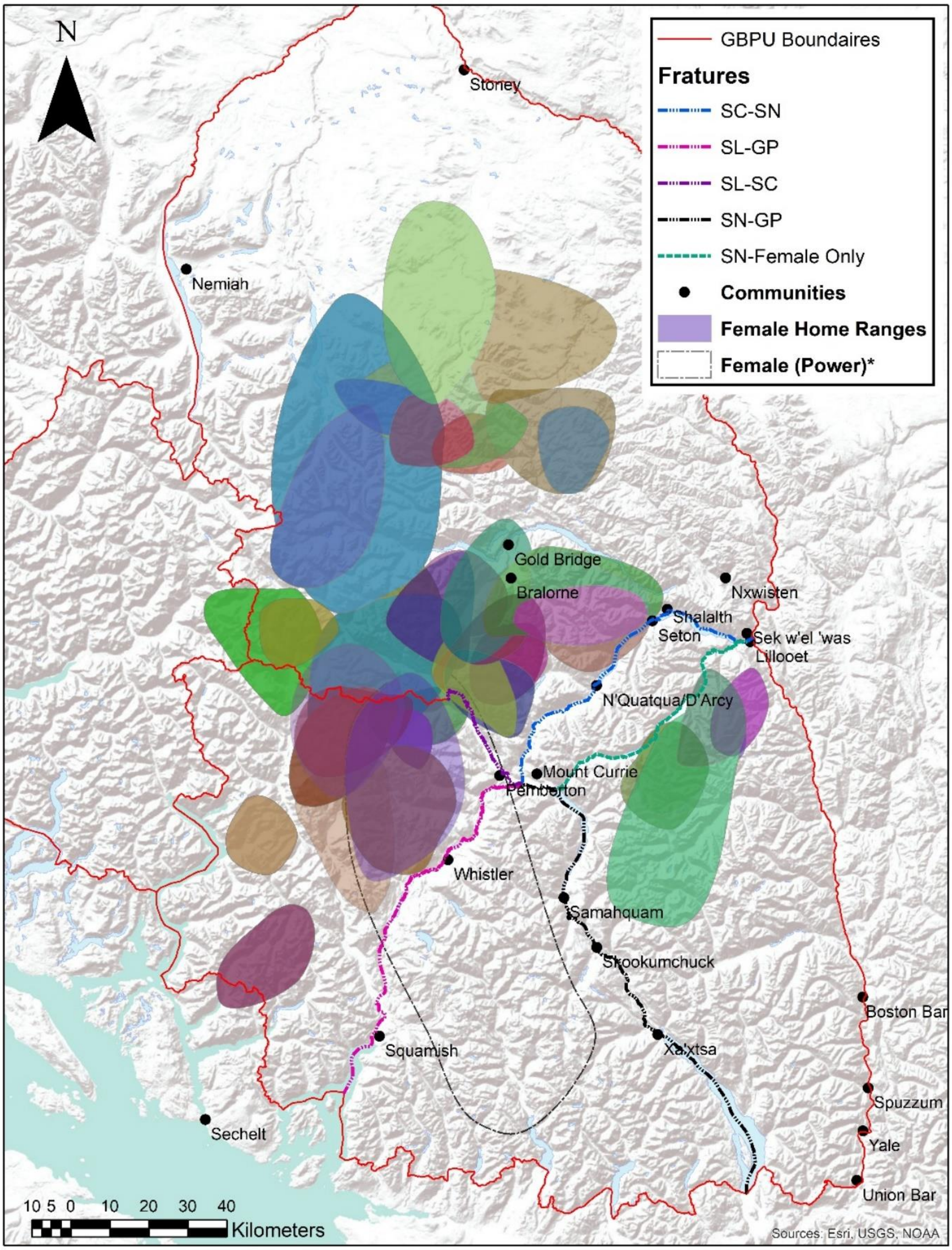

Figure 5: Adult female grizzly bear 95% minimum convex polygon home range boundaries. Fractures along population boundaries include the South Chilcotin—Stein Nahatlatch (SC-SN), Squamish-Lillooet – Garibaldi-Pitt (SL-GP), Squamish-Lillooet—South Chilcotin (SL-SC) which is only along a portion of the population unit boundary, and the Stein-Nahatlatch—Garibaldi-Pitt (SN-GP). Within the Stein-Nahatlatch population, there is an additional female-only fracture along Highway 99 (SN-female only).

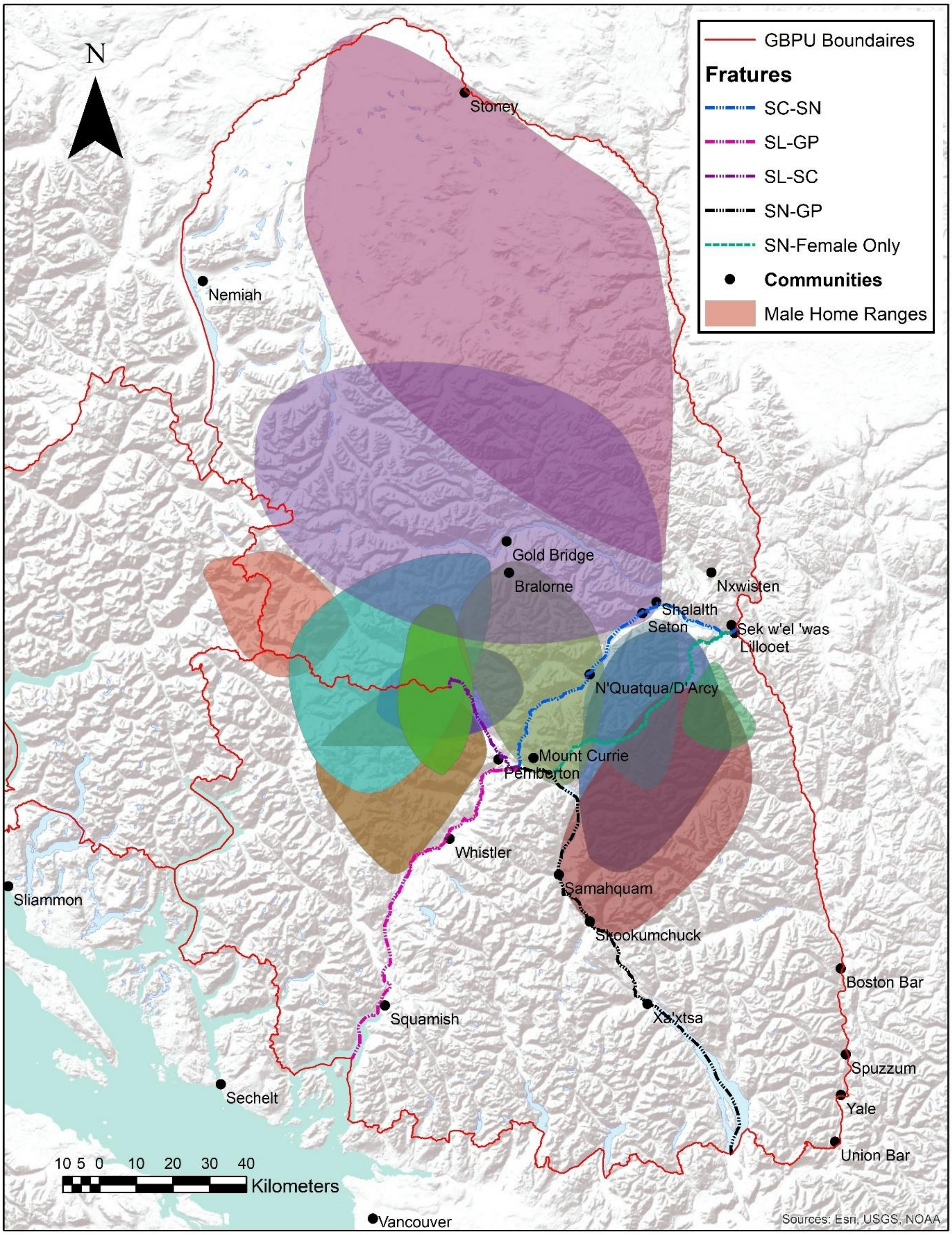

Figure 6: Adult male grizzly bear 95% minimum convex polygon home range boundaries. Fractures along population boundaries include the South Chilcotin—Stein Nahatlatch (SC-SN), Squamish-Lillooet – Garibaldi-Pitt (SL-GP), Squamish-Lillooet—South Chilcotin (SL-SC) which is only along a portion of the population unit boundary, and the Stein-Nahatlatch—Garibaldi-Pitt (SN-GP). Within the Stein-Nahatlatch population, there is an additional female only fracture along Highway 99 (SN-female only).

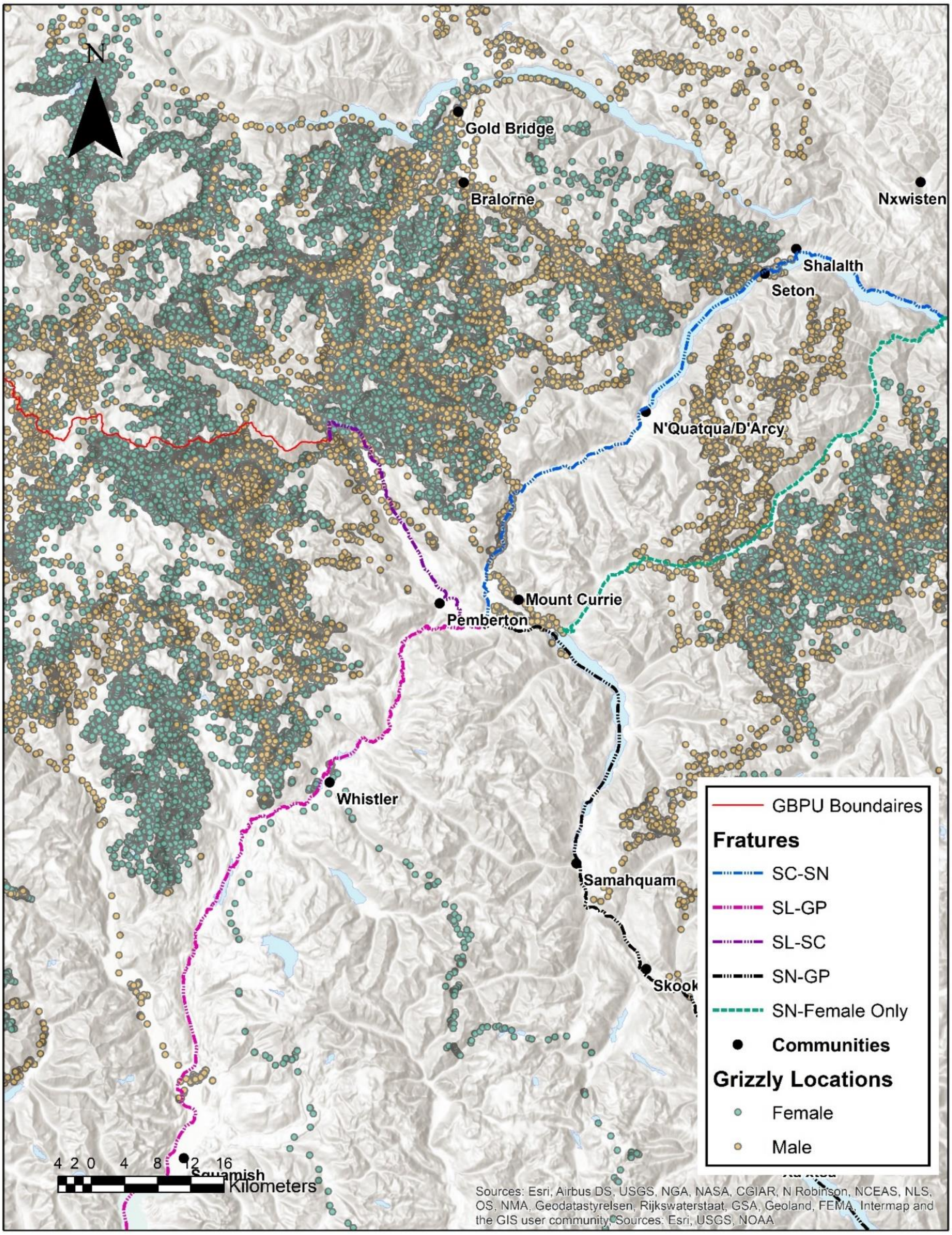

Figure 7: Grizzly bear locations at the intersection of the five main population fractures between the South Chilcotin (SC), Stein-Nahatlatch (SN), Squamish-Lillooet (SL), and Garibaldi-Pitt (GP) grizzly bear population units in southwestern British Columbia.

Connectivity

In this analysis, the degree of connectivity between core habitat areas is the least-cost path among core areas and is dependent on the distance and the resistance to movement (Figure 8). Within the occupied habitat, most of the resistance to movement results from natural features such as high mountains, icefields, and large lakes which are rarely, if ever, used habitats. Areas on the periphery of the study area also have high resistance to movement because of rarely used, often dry habitat, but also because there are no cores to connect with beyond the study area boundary. This result is most apparent in the eastern portion of the South Chilcotin population toward the Fraser River and as a result, this analysis is only applicable to areas within the study area and does not predict potential connectivity to possible core areas outside the study area. If the Fraser River and associated dry habitats is a boundary for dispersal or movement, then the connectivity predicted here is likely accurate, however, potential movements crossing the Fraser is not measured in this analysis. The high resistance to movement at the northern and western edges of the Toba-Bute population unit is likely an artifact of the study area boundary as well as the Homathko snowfield and extremely rugged mountains towards the headwaters of the Southgate River.

When current theory is applied to the cumulative resistance to movement, pinch points in connectivity, or areas of high movement density, are highlighted (Figure 9). These are useful for identifying areas of connectivity where there are barriers or constrictions such as between lakes or areas of human development in valley bottoms. Areas predicted in this way are thought to be analogous to dispersing animals without prior knowledge of the area, and thus the most likely locations for populations to reconnect across fractures. Mortality rates, however, are usually high where high-quality habitat overlaps with human density, potentially creating a population sink. Conserving, expanding, and actively managing pinch points in connectivity should provide additional habitat and, more importantly for grizzly bears, provide areas with lower mortality risk. Areas where a habitat corridor overlaps high building density should be targeted for attractant management and efforts to reduce mortality by increasing tolerance.

Knowing the location of pinch points in connectivity is most useful along the fractures between populations. These are the areas that bears are most likely to move through when moving or dispersing between populations. Because these are the locations where bears are most likely cross a fracture, they are also the areas where they are most likely to die in the fracture. Therefore, these areas should have priority for a variety of management actions directed at maintaining the integrity of these pinch points and reduce risks for bears passing through. For this reason, we will examine the major fractures in the study to estimate the location and importance of connectivity pinch points. We do not focus on the Toba-Bute population boundaries because there is little human density in this area and the effects of humans on connectivity to other populations is negligible there. Genetic research conducted by Apps et al. (2016) showed that there was little genetic distinction from other populations, indicating connectivity.

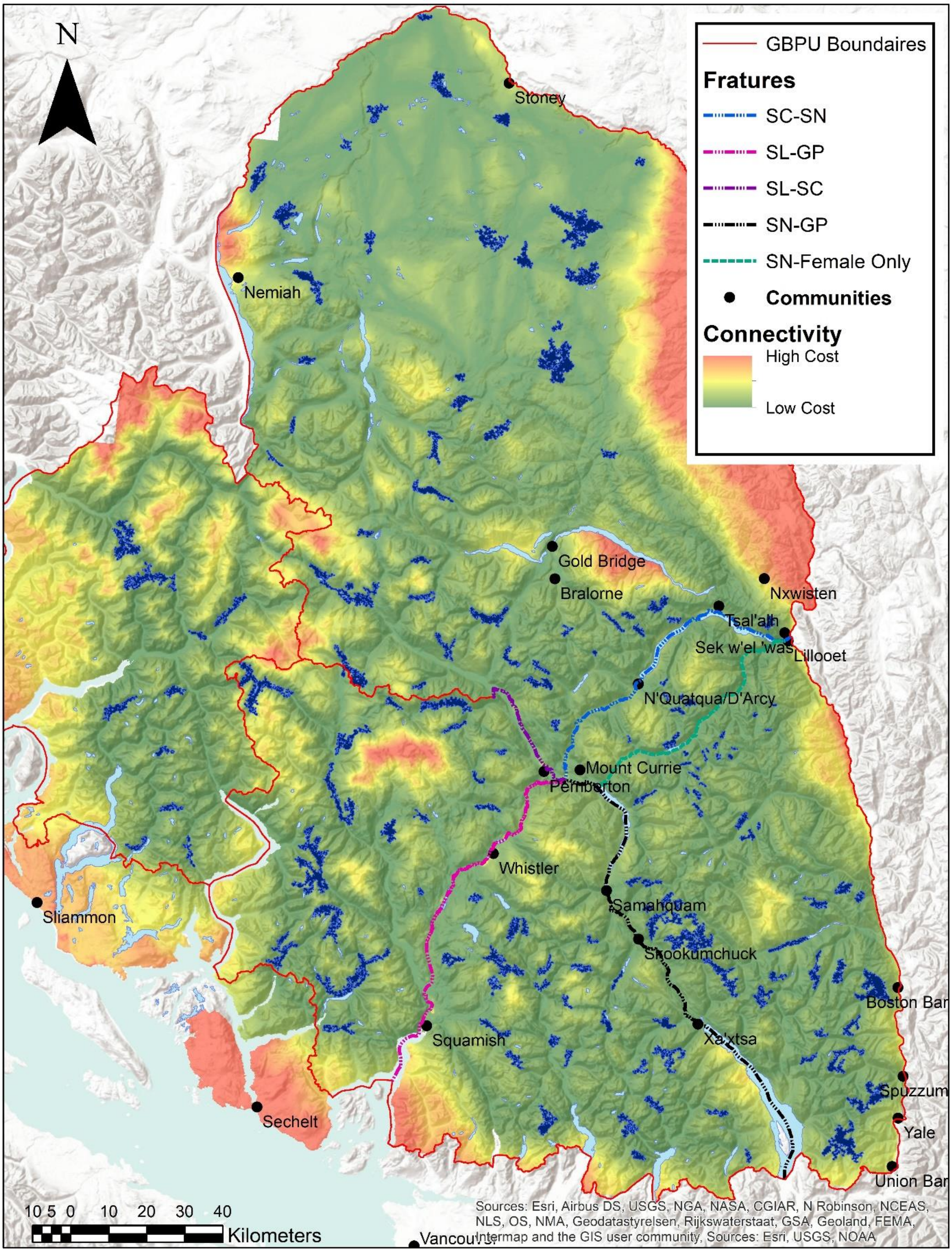

Figure 8: Cumulative cost-weighted distances between core habitat areas in grizzly bear populations in southwestern British Columbia. High costs on the periphery of the study area may be artifacts of analysis because core habitat areas outside the study area are not included in analysis.

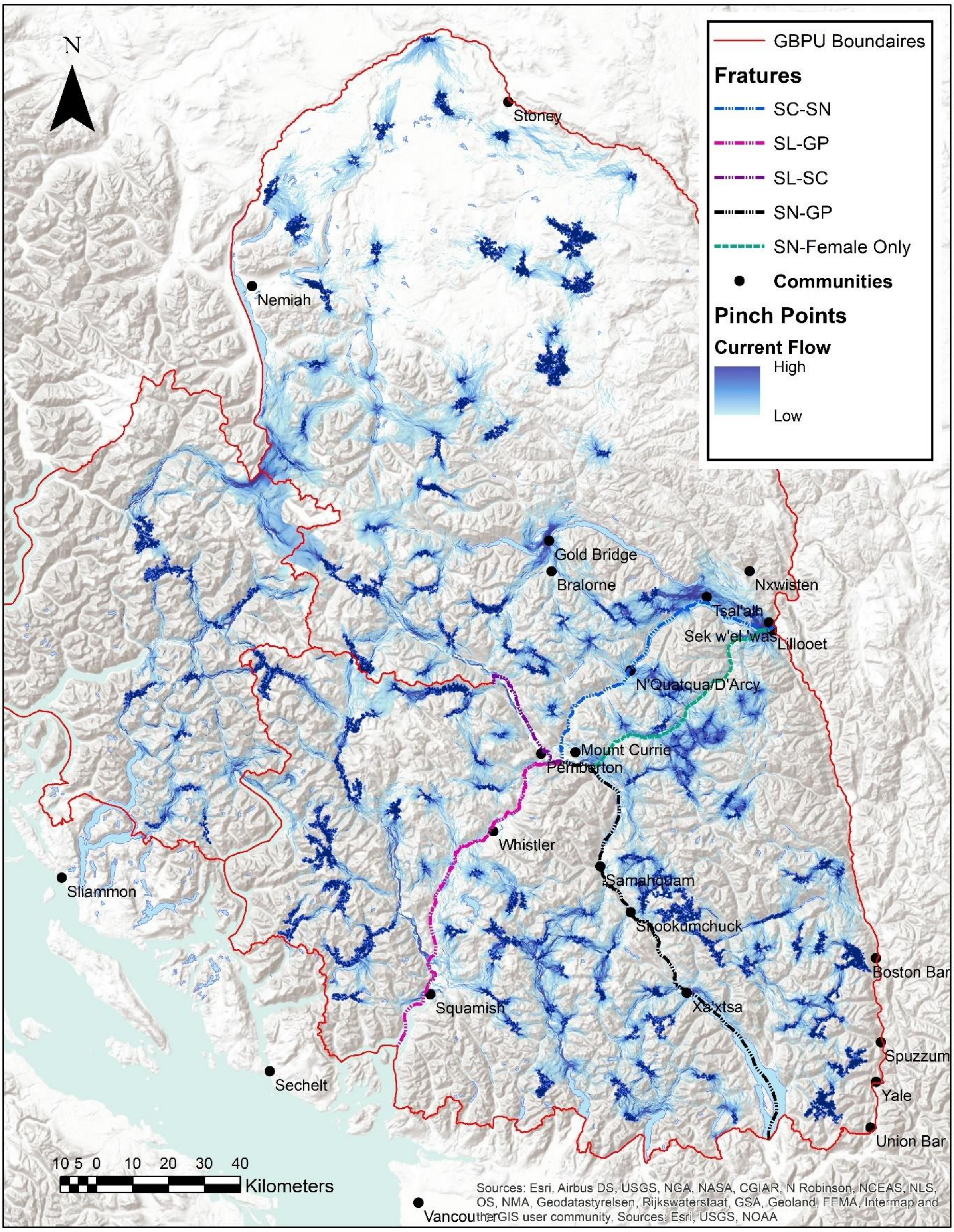

Figure 9: Pinch points in connectivity between core habitat areas and population fractures in southwest British Columbia.

South Chilcotin—Squamish-Lillooet

The South Chilcotin—Squamish-Lillooet population boundary is the most permeable of all interpolation boundaries considered here. Most of the boundary is in the Upper-Lillooet River drainage further upstream of the Pemberton Meadows agricultural area. Due to the large human footprint in the Pemberton Meadows agricultural area, connectivity is limited and only a few bears use the area. It is also highly probable that high historic grizzly bear mortality in the agricultural area is one cause of the contemporary exclusion of most adult females. This area is among the priorities for bear hazard assessments and actions to educate humans and reduce attractants (Ciarniello, 2020).

The spring habitat model suggests that most of the Pemberton Meadows area was high-quality habitat. Therefore, most of the restriction to movements suggested by the model would be due to of human influence and the absence of large core habitats nearby. As a result of these factors, pathways between these populations are mostly at the north-western end of the fracture where the human impact is least (Figure 10, 10A). A combination of forests, wetlands and regenerating areas dominated by tall shrubs provides vegetation for foraging as well as cover from humans. This is in part the result of the Pemberton Wetland Wildlife Management Area that protects some of the riparian habitat. Ciarniello (2020) discusses property-specific conservation options for this area. The linkages highlighted in this research support those recommendations.

Grizzly bear movement is predicted to be common along the agricultural areas at the base of the mountains on the southwest side of the valley and north of where the Ryan River drops into the valley (Figure 10 A). The southern end of the Pemberton Meadows has less bear activity but there are several points of potential connectivity where building density is low (Figure 10B). The existing conservation areas that prioritize conservation of wetlands and sloughs, contribute to the connectivity between populations. Expansion of linkage areas in the Pemberton Meadows will also likely increase to grizzly bears' access to salmon.

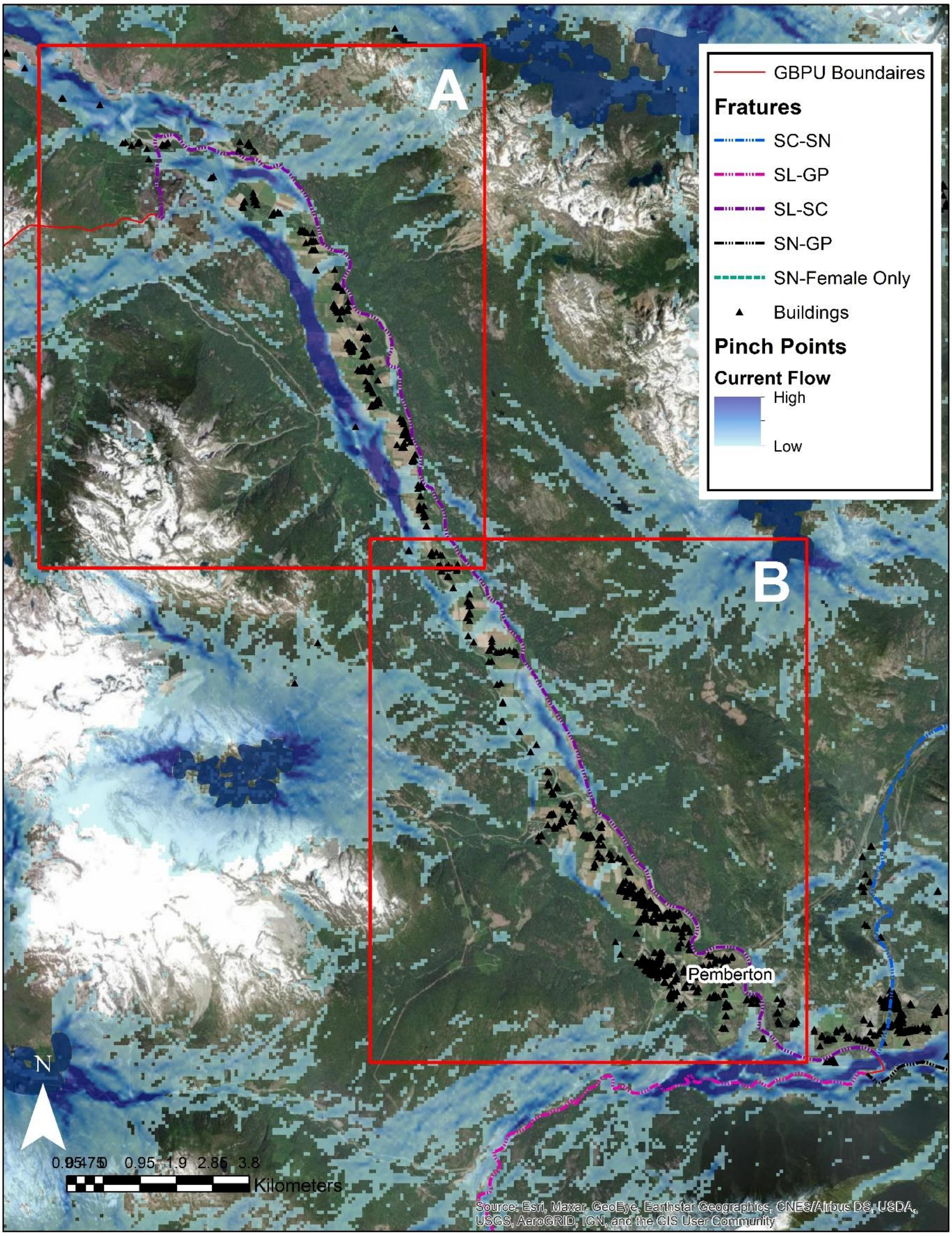

Figure 10: Pemberton Meadows is a partial population fracture between the South Chilcotin and Squamish-Lillooet grizzly bear populations in southwest BC. Inset maps of areas A and B in figures 11 and 12 respectively.

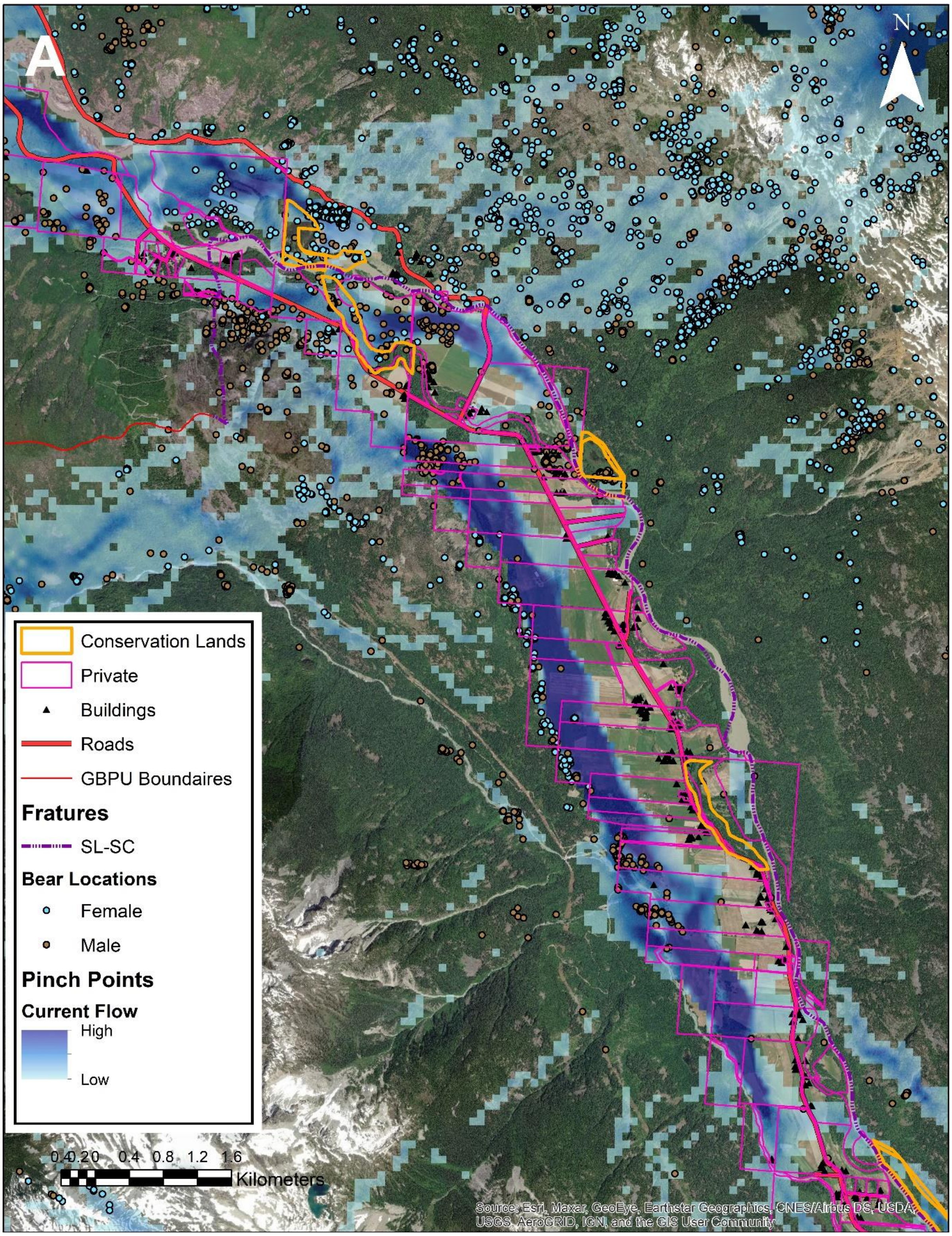

Figure 11: Interpopulation connectivity in the north-western part of Pemberton Meadows area that divides the South Chilcotin and Squamish-Lillooet grizzly bear populations in southwestern British Columbia. See Figure 10 for location reference.

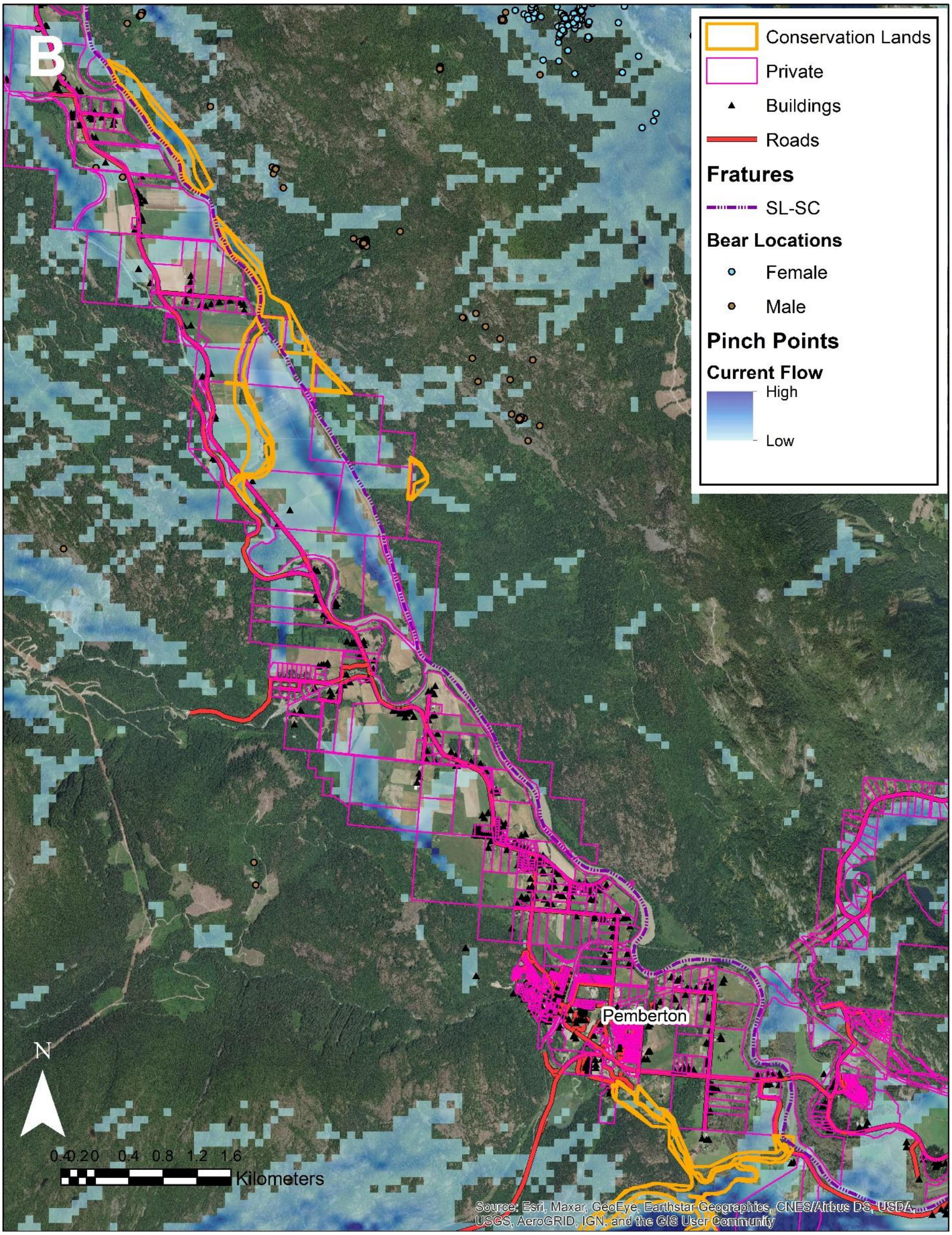

Figure 12: Interpopulation connectivity in the southern part of Pemberton Meadows area and around the village of Pemberton that divides the South Chilcotin and Squamish-Lillooet grizzly bear populations in southwestern British Columbia. See Figure 10 for location reference.

South Chilcotin—Stein-Nahatlatch

The South Chilcotin—Stein-Nahatlatch population boundary stretches between the Lillooet River valley near Mount Currie to the town of Lillooet on the Fraser River (Figure 11). This area was the focus of another linkage analysis conducted in 2018 (McLellan, 2018) but will be summarized here for consistency within the study area. The western part of the fracture follows Pemberton Portage Rd between Mount Currie and the communities of D'Arcy and N'Quatqua. Two large lakes span the remaining 45 km to Lillooet with only the communities of Seton and Shalalth.

Grizzly bear movement between the populations across this fracture has been rare. Except for one translocated female, interpopulation movement across this fracture has been limited to a few male bears and none were collared when they crossed. The genetic distance between the Stein-Nahatlatch bears and bears from other populations suggests that this population fracture is many generations old (Apps et al., 2016; McLellan et al., 2021, 2019). Fortunately, genetic sampling has confirmed that some males have crossed the fracture and there have even been recent cross-population reproductive events, including a cub born in the Stein-Nahatlatch with a father that came from the South Chilcotin. Nevertheless, the Stein-Nahatlatch population remains small (<25 individuals), mostly inbred, and has been in decline (McLellan et al., 2021, 2019), therefore maintaining connectivity to this population is imperative for the population's recovery and long-term persistence.

Pinch points in connectivity in this area are strongly influenced by the lakes and the Fraser River which is a boundary due to the river, canyon, dry habitat and agricultural development and rural settlements on the benches (Figure 11A). No collared bears crossed the Fraser River, nor is there genetic evidence of connectivity there. There is a large pinch point between the end of Seton Lake and the Fraser near the town of Lillooet. Despite the relatively low building density, this area has a dam, hydro-electric facility, canal, sawmill, highway, railway, spawning channel, picnic area, campground, and dry precipitous slopes on either side. Although the spawning channel may eventually attract grizzly bears, the potential for developing meaningful conservation areas here will be limited by the current permanent development and geographic restrictions. See Appendix 3 for more detailed maps.

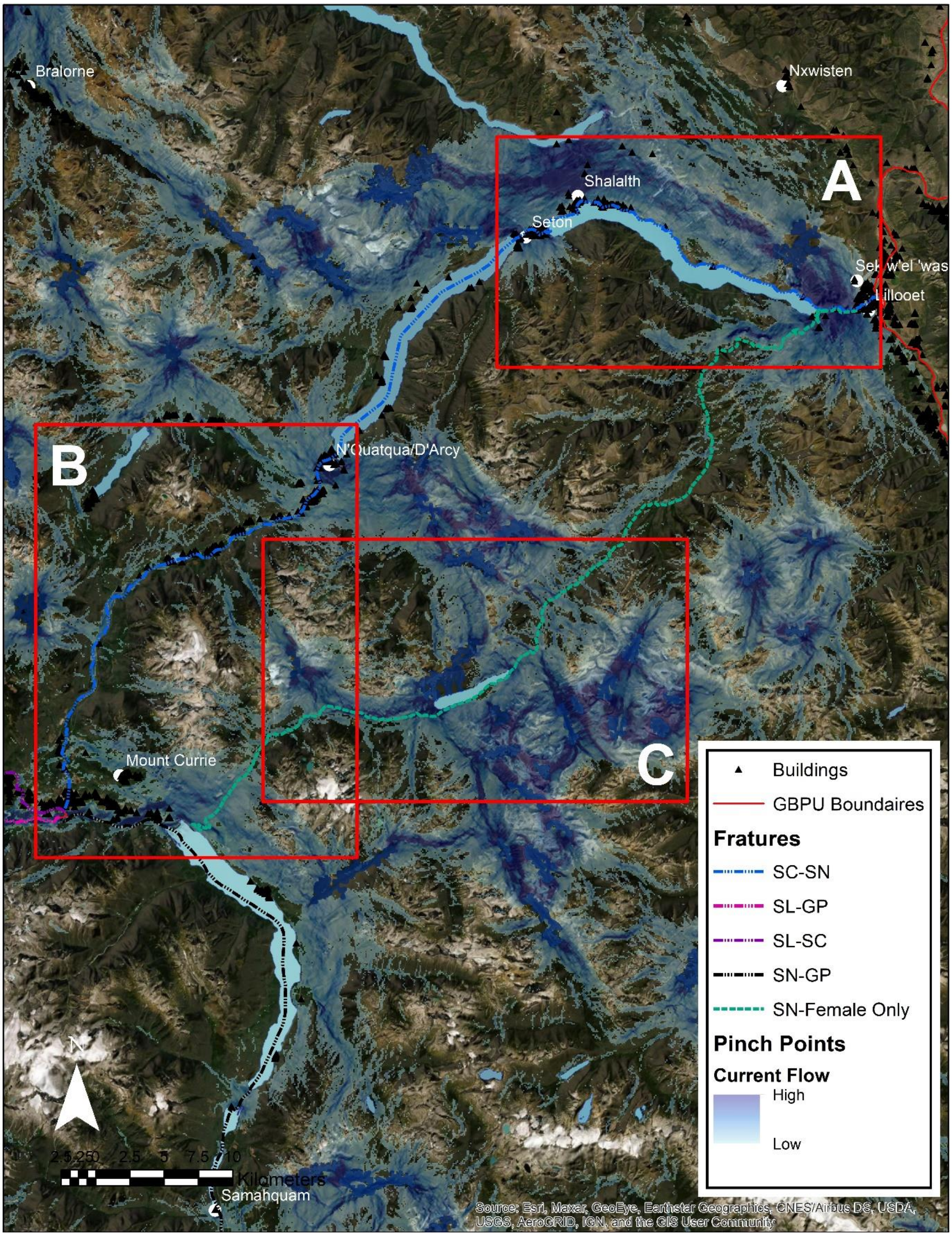

Figure 13: South Chilcotin—Stein-Nahatlatch population fracture and the Stein-Nahatlatch female only fracture following Highway 99 between Mount Currie and Lillooet.

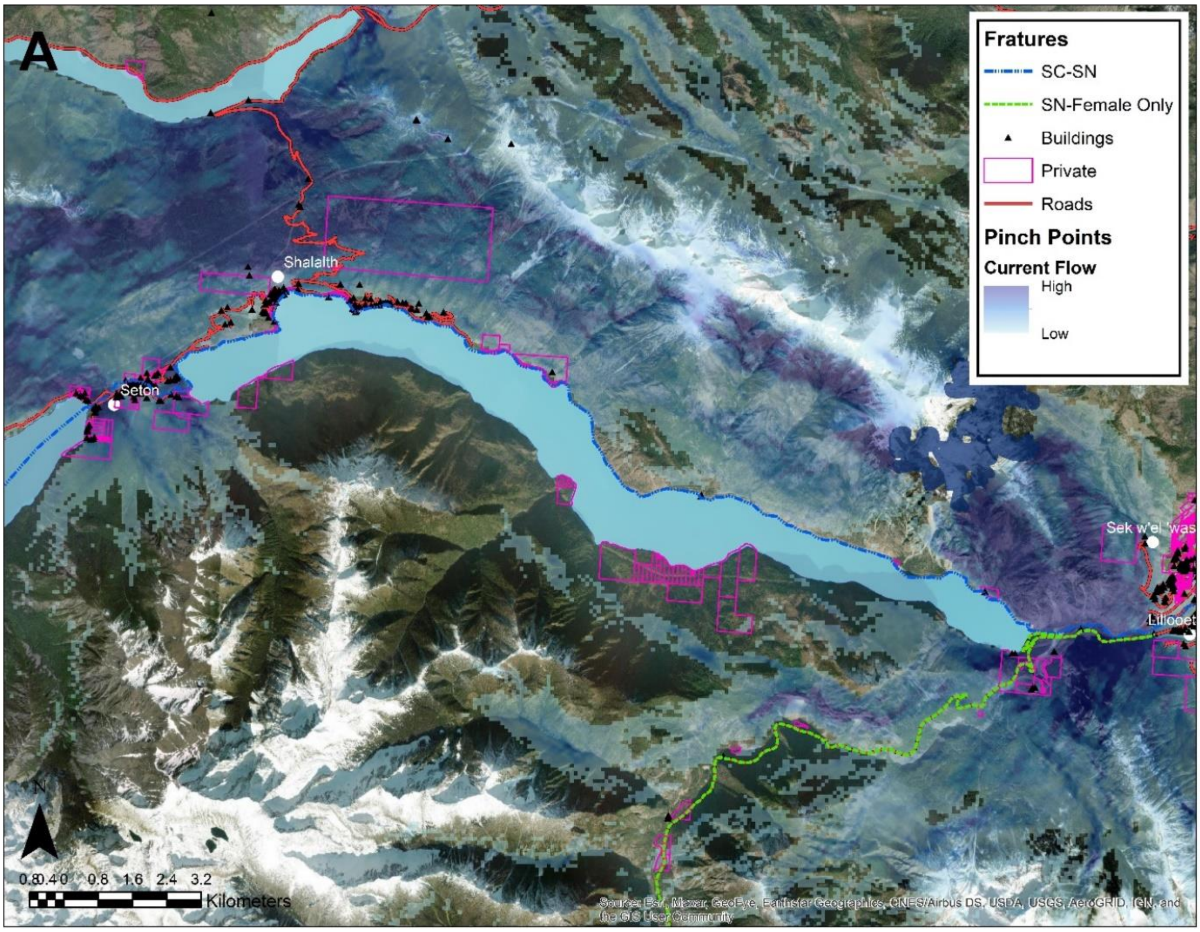

Figure 14: A portion of the South Chilcotin—Stein-Nahatlatch population fracture Seton Portage and Lillooet.

Twenty-one kilometres west, at the other end of Seton Lake, a 2.1 km stretch of land, separates Seton from Anderson Lake. This area also forms a natural pinch point in connectivity between the populations (Figure 11A; Appendix 3). About 80 people live in the area, mostly in the villages of Seton and Shalalth. This area is a priority for protecting remaining linkage habitats because of its proximity to heavily used core habitats in the Whitecap drainage of the South Chilcotin population and a probable source of naturally dispersing bears. Although much of the isthmus has human development, residences, and hobby farms, there are natural spaces remaining near the confluence of the Whitecap and Seton Rivers. Connectivity via this pinch point will be tenuous and conflicts are likely. A successful linkage in this area will require ongoing commitment and encouragement for locals to manage attractants, livestock and fruit trees (Ciarniello and Patrick, 2019). This is a priority area for hazard assessment and management as well as conservation from further development.

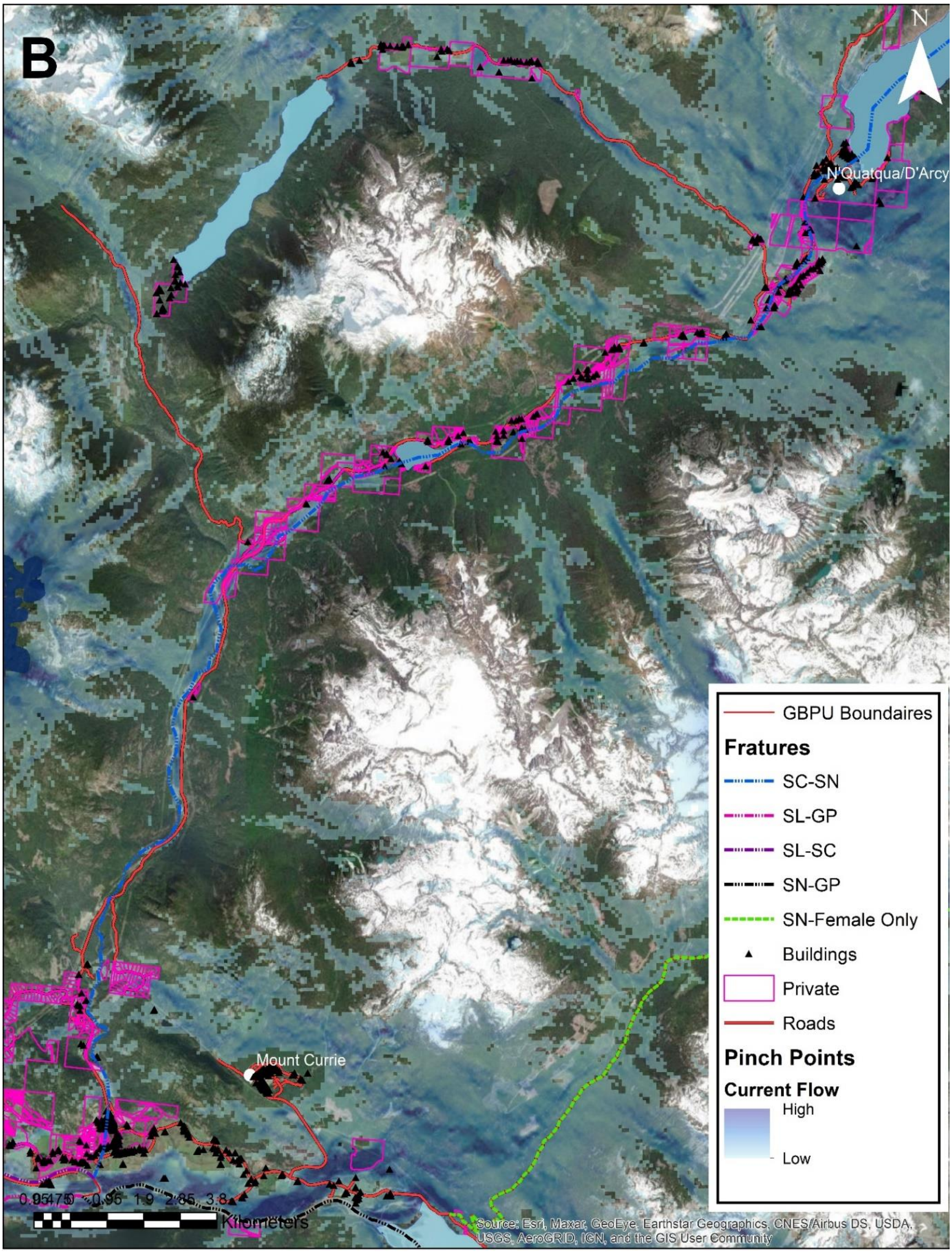

Figure 15: A portion of the South Chilcotin—Stein-Nahatlatch population fracture between D’Arcy/N’Quatqua communities at the head of Anderson Lake and Mount Currie.

At the other, southwestern end of Anderson Lake, the physical geography funnels potential linkage zones near the communities of N'Quatqua/D'Arcy and Devine. The confluence of the Haylmore,Spruce, and Blackwater Creeks with Gates Creek provides a natural corridors through the area. Although several previously large private pieces of private land in this area have been subdivided in the past few years, potential connectivity is potentially maintained by a few remaining large and mostly undeveloped pieces of private land (Figure 13B; Figure 15, Appendix 3). Like Seton Portage, the proximity to human settlement highlights the importance for secure habitat and ongoing conflict mitigation (Ciarniello and Patrick, 2019).

Moving westward along the fracture, most of the valley bottom is private land until Pool Creek and where the Birkenhead River parallels the highway. Fortunately, many of the private land parcels span the narrow valley reducing the overall human density and increasing the potential for meaningful conservation efforts. However, these parcels are increasingly being bought and subdivided, increasing human density and the cost of protecting the area for wildlife corridors.

The 12 km between Pool Creek and Owl Creek along the Birkenhead River are the least developed in the SC-SN fracture. Furthermore, the availability of spawning salmon in the fall and the proximity a large huckleberry field in Tenquille Drainage increase the value of this area as a potential linkage area between populations.

The "female-only" population fracture following Highway 99 between Mount Currie and Lillooet is currently undeveloped and male bears frequently moved across the fracture (Figure 11C). The area has many recreation sites and is becoming increasingly popular for camping, hiking, motorcycle touring, and sight-seeing. Maintaining connectivity across this fracture will involve preventive actions. Ensuring no permanent infrastructure development in this area including recreation development such as trails, cabins, parking and camping will be necessary for maintaining the integrity and security of the habitat for population connectivity.

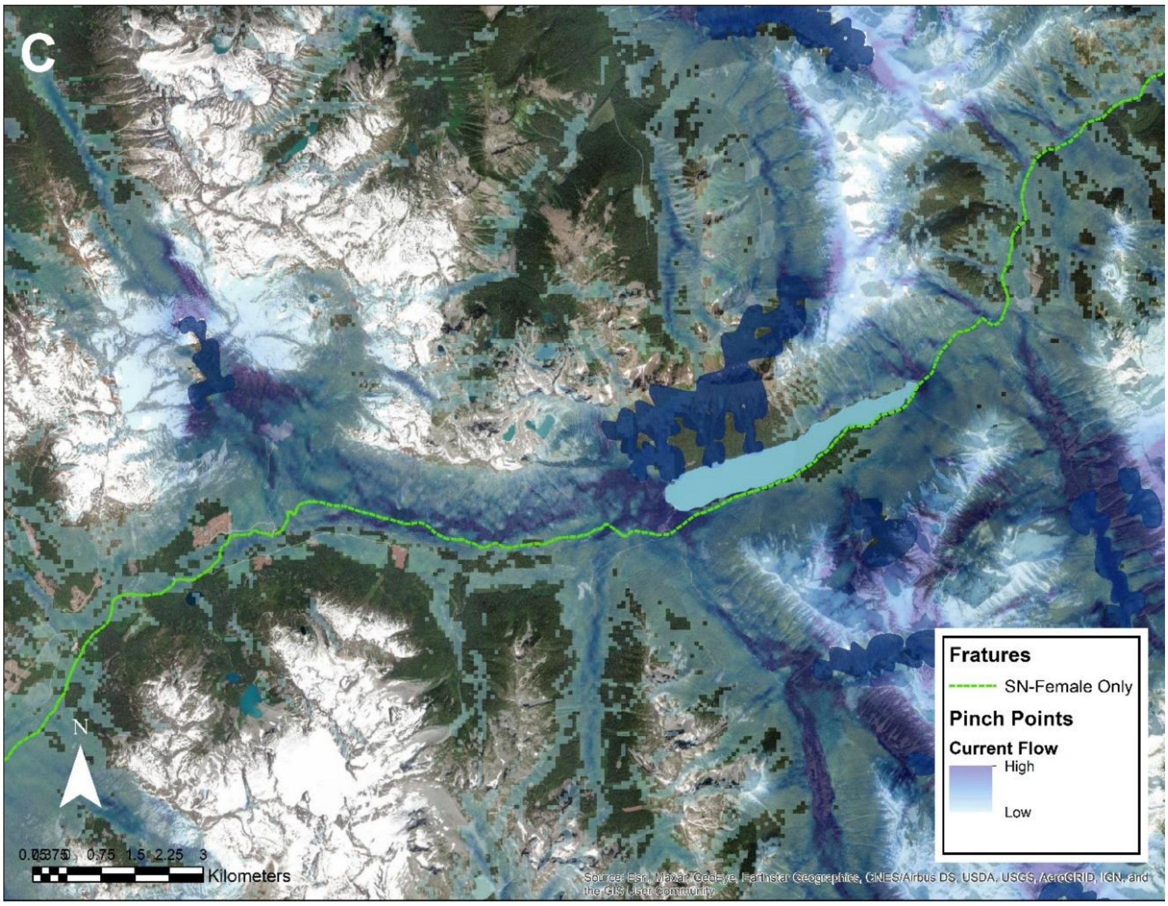

Figure 16: Second population fracture between the South Chilcotin—Stein-Nahatlatch grizzly populations uncrossed by female grizzly bears. This fracture follows Highway 99 between Lillooet and Mount Currie.

Squamish-Lillooet—Garibaldi-Pitt

The Sea to Sky Highway between Vancouver and Whistler is one of the busiest highways in British Columbia and it divides the growing Squamish-Lillooet grizzly population from the nearly extirpated Garibaldi-Pitt popualtion unit (Figure 12). Unlike the other interpopulation fractures in this analysis, most of the human density is clustered near Squamish, Whistler, and Pemberton, and there are long sections of undeveloped crown land between communities.

Most core habitat areas in the Garibaldi-Pitt unit are in the southern end and the highest potential for connectivity are via Rutherford creek and the broad riparian areas at the base of Mount Currie and the area between the Cheakamus river and Callahan Valley (Figure 12). Toward Squamish there are connectivity pinchpoints on the south end of Daisy lake and north of Brakendale (Figure 12). Two collared bears crossed the population fracture, one male crossed north of Squamish near the confluence of the Squamish and Cheakamus and the adult female that walked around the Garibaldi-Pitt popualiton unit crossed through the town of Whistler both times.

Most of the Garibaldi-Pitt population unit is in Garibaldi, Golden Ears, or Pinecone Burke Provincial Parks and although this popualtion unit is relatively protected from resource extration inducstry, this area receives millions of visitors each year. Reesablishing a viable population in this unit will require mantaining linkage areas and ensuring that there are secure core habitats in the Garibaldi-Pitt, possibly with reduced disturbance from recreation.

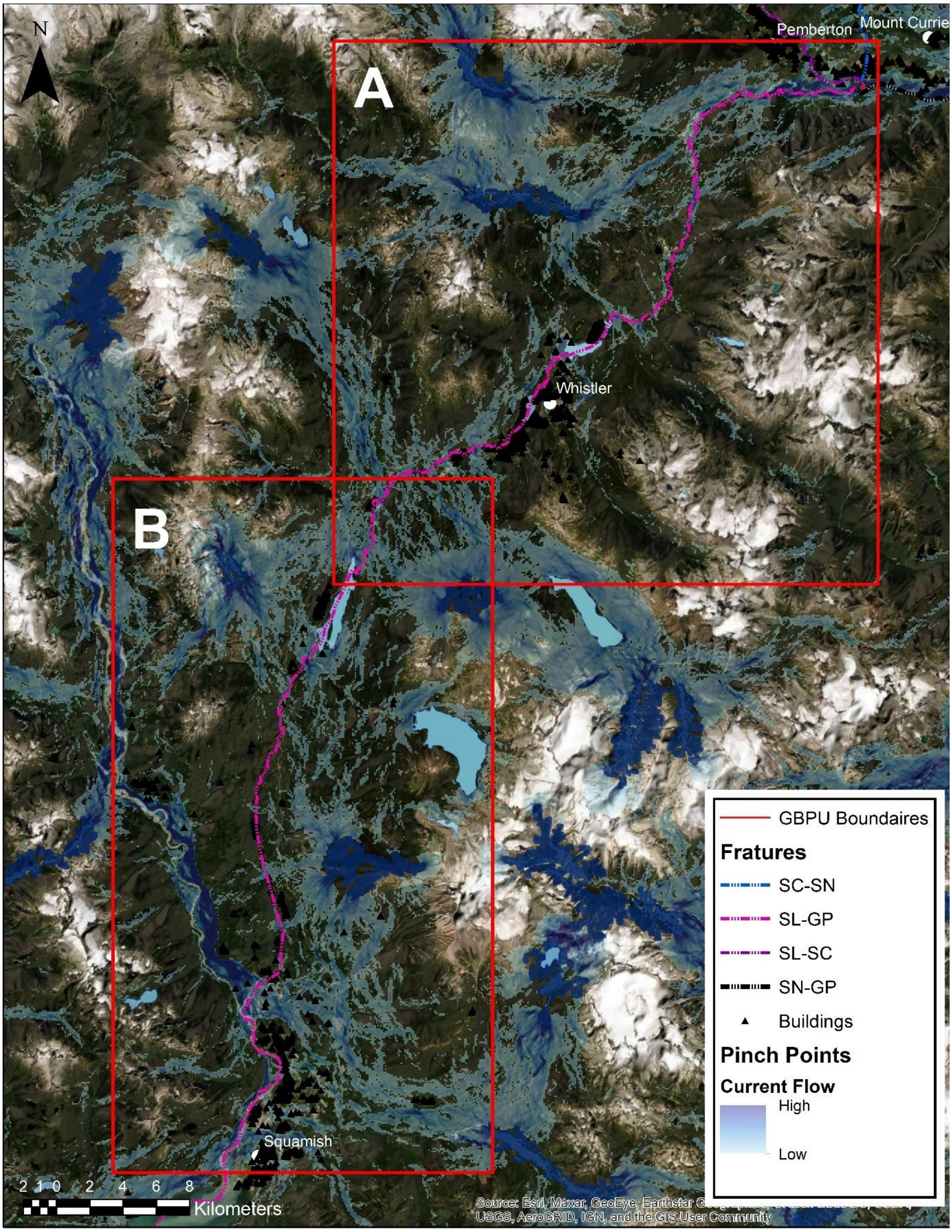

Figure 17: Squamish Lillooet—Garibaldi-Pitt population fracture following Highway 99 between Squamish and Pemberton.

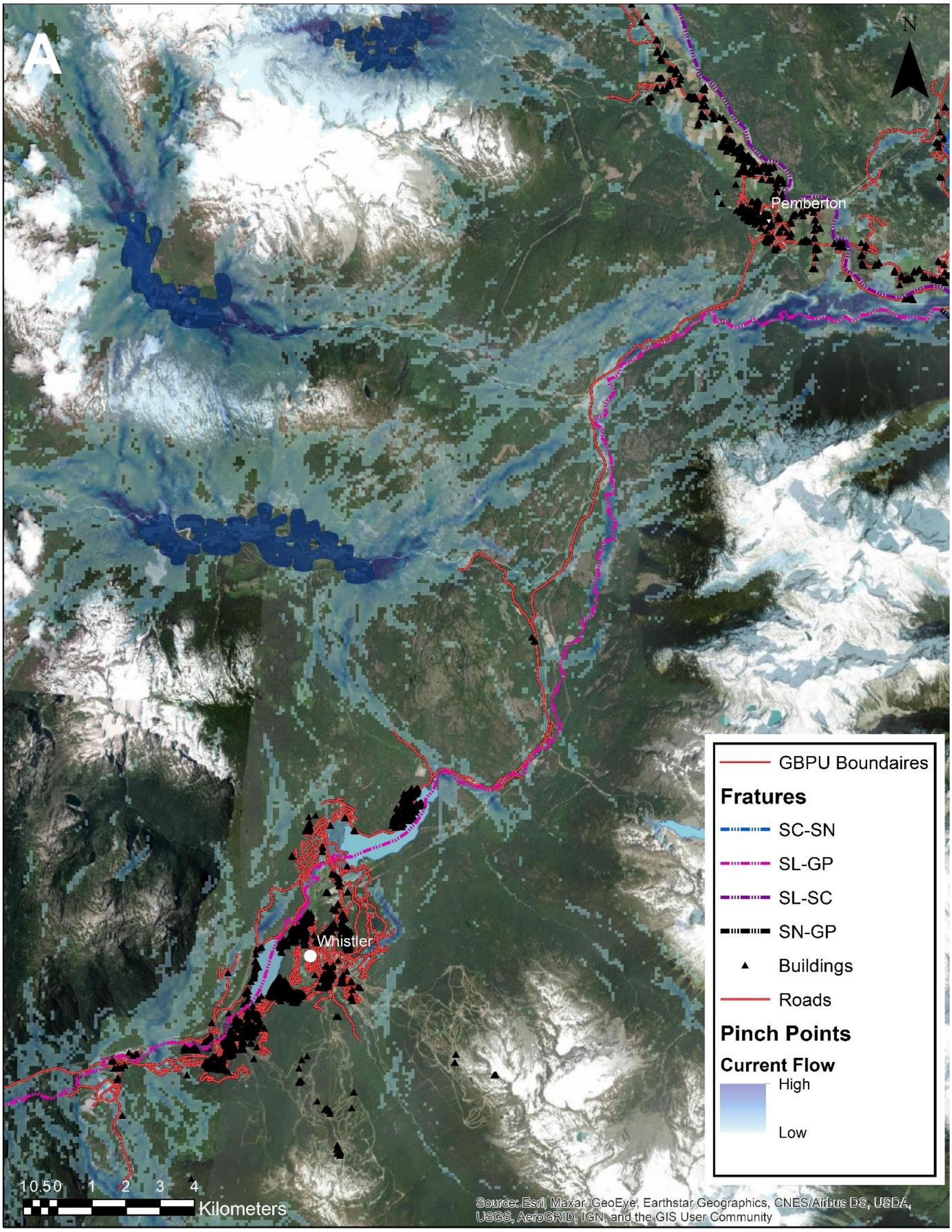

Figure 18: The northern portion of Squamish Lillooet—Garibaldi-Pitt population fracture following Highway 99 between Whistler and Pemberton.

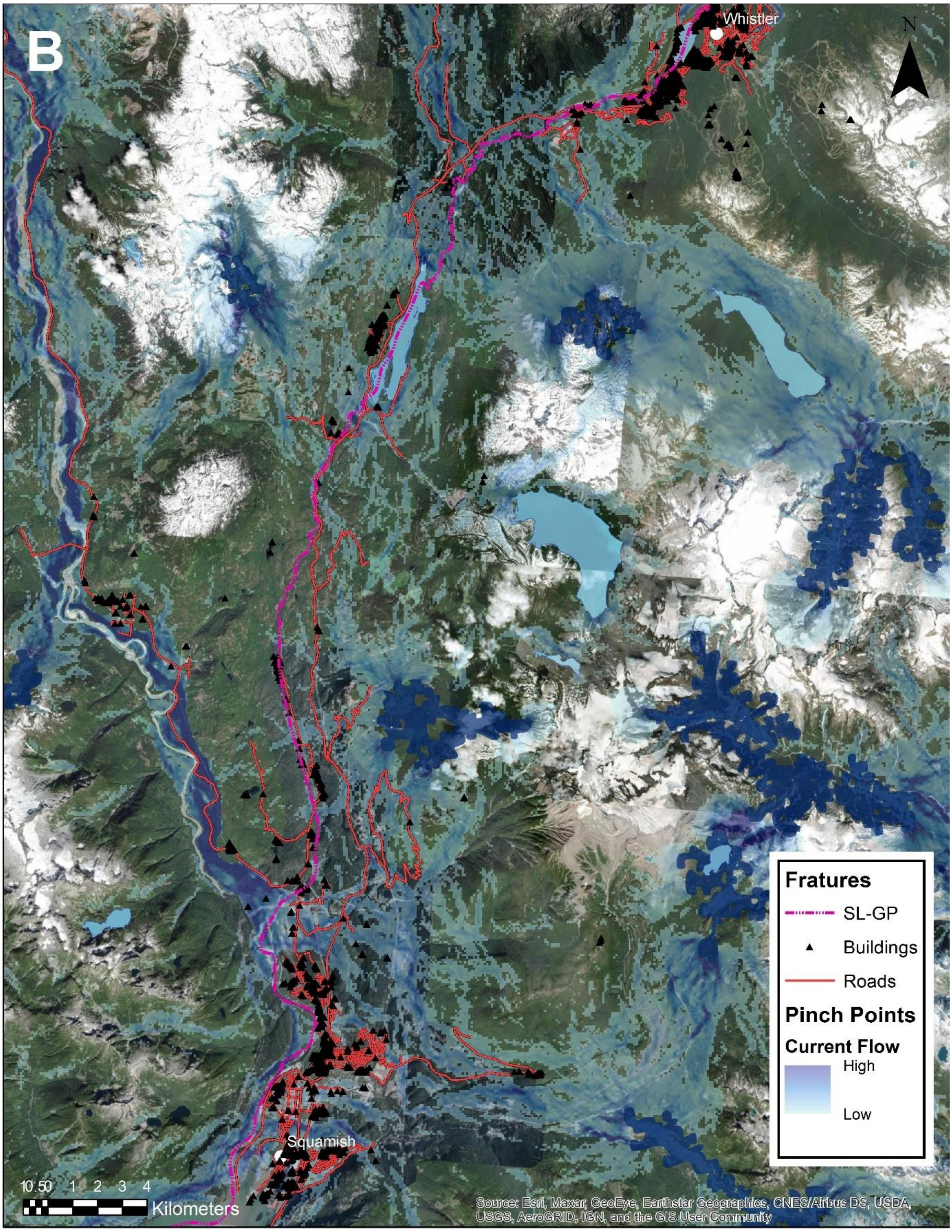

Figure 19: The southern portion of Squamish Lillooet—Garibaldi-Pitt population fracture following Highway 99 between Squamish and Whistler.

Stein-Nahatlatch—Garibaldi-Pitt

The eastern side of the Garibaldi-Pitt population unit is relatively undeveloped compared to the Squamish-Pemberton corridor and receives a fraction of the visitors. Linkage with the Stein-Nahatlatch population is most likely concentrated around the end of each lake and near the community of Skookumchuck (Figure 13). Maintaining connectivity in this area will be important as grizzlies begin to recover in the two neighbouring populations.

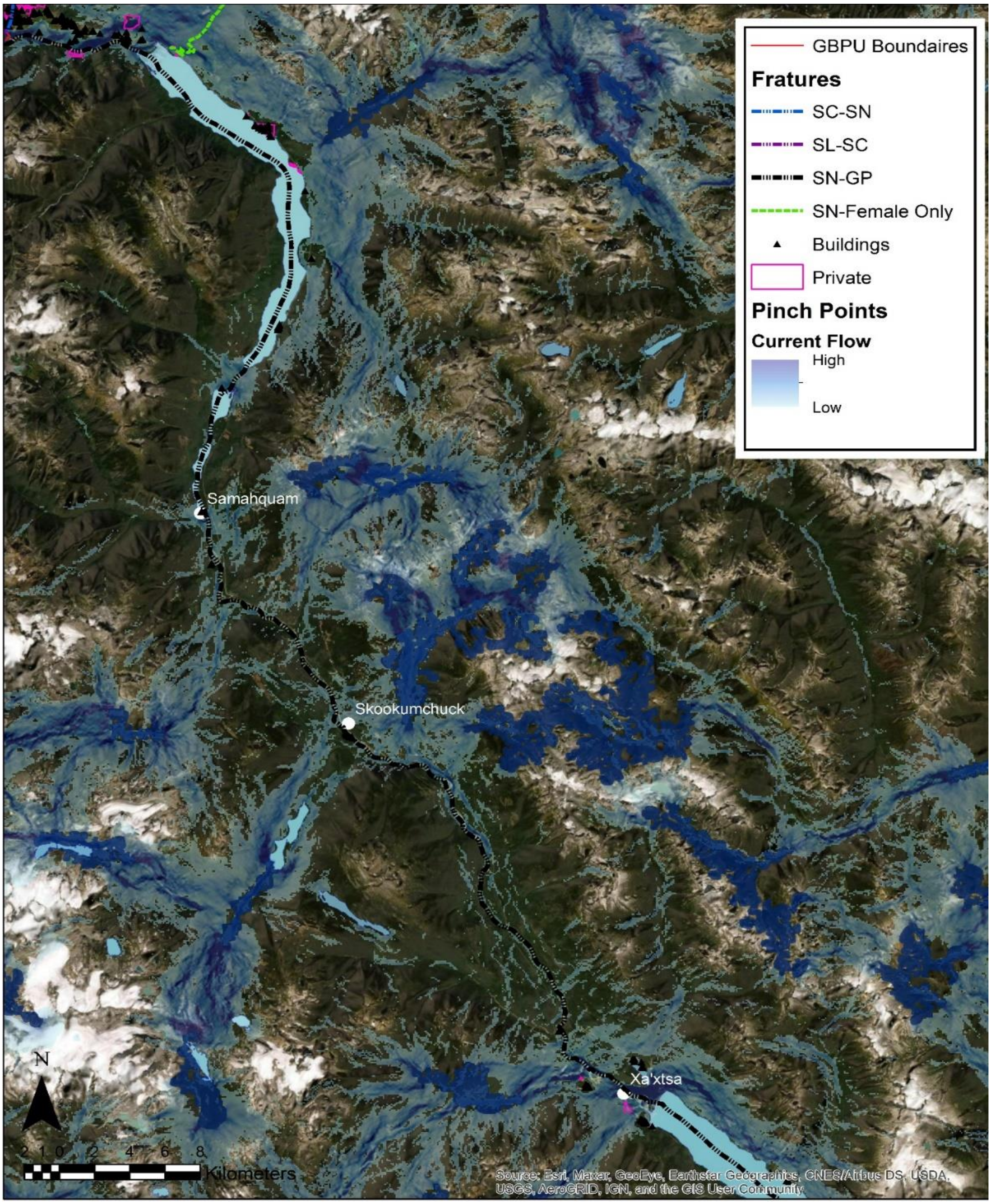

Figure 20: The Garibaldi-Pitt—Stein-Nahatlatch population fracture between Lillooet Lake and Harrison Lake.

CONCLUSIONS AND RECOMMENDATIONS

Recovering grizzly bears and maintaining viable populations in the southwestern extent of their range in North America is dependent on long term interpopulation connectivity. The recent population growth in the South Chilcotin and Squamish-Lillooet populations indicates that recovery is possible in the region but steps toward recovery vary depending on the current attributes of each fracture and the populations they divide.

Conservation in and around the growing Squamish-Lillooet and South Chilcotin will require ongoing bear-human interaction management. Historically, areas with high levels of human development were inhospitable to bears because of human-caused mortality. As attitudes toward coexistence change and tolerance increases, the possibility that bears will survive to use habitats linking populations also increases. The objective for these populations is to ensure that the current fractures do not become population sinks and that mortality risk is low enough that bears using low-elevation fracture zones survive.

Conservation in the small and isolated Stein-Nahatlatch and nearly extirpated Garibaldi-Pitt population will require conservation efforts within the population as well as in the fractures that separate them from the recovering populations. Within population conservation efforts include access management to reduce human-caused mortality and protect access to core habitats as well as population augmentation to increase genetic diversity and the number of reproducing females. Efforts in the fracture are vital for long-term resilience to directional and random environmental changes. **As a result, the most important fractures to restore are the South Chilcotin—Stein-Nahatlatch fracture between Mount Currie and Lillooet via N'Quatqua/D'Arcy to Mount Currie and the Squamish-Lillooet—Garibaldi-Pitt between Squamish and Pemberton.**

The linkage zones predicted in this analysis assume that current human development and density are the primary factors limiting bear survival. Resistance to movement and connectivity is defined by the permanent infrastructure on the landscape as a surrogate for human presence and potential intolerance to coexistence. However, it does not consider the rapidly expanding use of remote areas for recreation. Over the last decade, human use of remote areas has rapidly increased and most of the impacts on wildlife are speculative. We do not understand the impacts of backcountry recreation in and around core habitats on survival and reproduction of grizzly bears. Therefore, investing in research to understand these impacts and best management practices for mitigating them will likely be imperative for population sustainability and recovery in the future.

We recommend the application of the connectivity models built in this analysis to compare alternative conservation actions and use as a decision-making tool for spatially specific conservation efforts. Population connectivity at the pinch point scale across partial and complete population fractures can be compared and weighted using the resulting connectivity models. These models can also be applied to within population connectivity and assessing the impacts of potential developments for industry or recreation.

Developing and conserving interpopulation connectivity will only be successful if information and planning are a collaborative effort beginning with leadership and direction from local First Nations communities especially for specific fracture locations. Communication and collaboration with provincial and regional governments, and other environmental government (e.g., BC Parks) and non-government organizations will be imperative for broad scale synthesis of conservation goals. At finer scales collaboration with community conservation groups and local initiatives such as Bear Aware will improve the long-term sustainability of developing and maintaining connectivity in the region.

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Appendix 1: Resource Selection Functions

Table A1-1 Spatial covariates used for seasonal RSF model development for grizzly bear habitat in southwestern British Columbia, Canada.

Covariates	**Code**	**Description**	**Data Type**
Climate Covariates	dd_0	Degree-days below 0°C	Continuous
	dd_18	Degree-days below 18°C	Continuous
	dd18	Degree-days above 18°C	Continuous
	dd5	Degree-days above 5°C	Continuous
	nffd_sp	Spring number of frost-free days	Continuous
	dd_0_sp	Spring degree-days below 0°C	Continuous
	dd18_sm	Summer degree-days above 18°C	Continuous
	dd5_sp	Spring degree-days above 5°C	Continuous
	map	Mean annual precipitation (mm)	Continuous
	ppt_at	Autumn precipitation (mm)	Continuous
	ppt_sp	Spring precipitation (mm)	Continuous
	ppt_wt	Winter precipitation (mm)	Continuous
	ppt_su	Summer precipitation (mm)	Continuous
	pas_wt	Winter precipitation as snow (mm)	Continuous
Green	EVI	Greenness	Continuous
	δEVI	Seasonal greenness change	Continuous
Topographical	south	Southerliness	Continuous 0 to 1
	west	Westerliness	Continuous 0 to 1
	sol_rad	Solar Radiation	Continuous
	cti	Wettness	Continuous
	tri	Ruggedness	Continuous
	slope	Slope	Continuous
Crown Closure	canopy	Crown Closure	Continuous %
Whitebark pine	WBP	Whitebark pine cover	Continuous %
Open road density	OR_dens	Road density in km/km^2	Continuous

Table continued next page.

Table A1-1 Continued.			
Covariates	**Code**	**Description**	**Data Type**
Disturbance History	F <15	Fire less than 15 years	0 or 1
	F 15to30	Fire 15 to 50 years	0 or 1
	F 51-80	Fire 50 to 80 years	0 or 1
	F.>80	Fire over 80 years	0 or 1
	H_<10	Harvest less 10 years	0 or 1
	H_10to30	Harvest 11 to 30 years	0 or 1
	H_30to50	Harvest 11 to 30 years	0 or 1
	H_>50	Harvest over 50 years	0 or 1
Landscape Cover (HAB_COV)	CWH	Cedar-Western Hemlock	0 or 1
	ESSF	Engelmann-Spruce-Subalpine Fir	0 or 1
	IDF	Interior Douglas Fir -Ponderosa Pine	0 or 1
	MH	Mountain Hemlock	0 or 1
	SBPS	S	0 or 1
	MS	Montane Spruce	0 or 1
	AVY	Herb dominated avalanche chutes	0 or 1
	ALP	Herb dominated alpine	0 or 1
	SHRUB_AVY	Shrub-dominated avalanche chutes	0 or 1
	HEATHER	Heather dominated alpine	0 or 1
	KRUM	Krumholtz	0 or 1
	WETLAND	Wetland	0 or 1
	ROCKI	Rock and Ice	0 or 1
	WATER	Water	0 or 1
	ANTH	Anthropogenically modified	0 or 1
Soil Parent Material (Soil)	GF	Glaciofluvial	0 or 1
	FL	Fluvial	0 or 1
	LA	Lacustrine	0 or 1
	CO	Colluvium	0 or 1
	TI	Till	0 or 1
	BR	BedRock	0 or 1
	GL	Glaciolacustrine	0 or 1
	O	Organic	0 or 1

** Fire and Harvest disturbance categories were determined in modelling process.

Table A2-2 Spiring resource selection model (May-June) developed from GPS grizzly bear locations in the southern Coast Mountains of British Columbia. Covariates are scaled for comparison.

Category	Variable	β	SE	P val
Environmental	Green (EVI)	1.79	0.02	<0.0001
	Solar Radiation	1.07	0.01	<0.0001
	Westerliness	0.15	0.01	<0.0001
	Slope	0.27	0.01	<0.0001
	Canopy closure	-0.15	0.01	<0.0001
	Whitebark pine cover	0.07	0.01	<0.0001
Climate	Summer days below 18°C	-0.18	0.02	<0.0001
	Winter precipitation as snow	-0.23	0.02	<0.0001
Landscape Cover (Ref= Alpine Herb)	Anthropogenic	-0.90	0.15	<0.0001
	Avalanche chutes	0.62	0.03	<0.0001
	Shrub-Avalanche Chute	-0.28	0.04	<0.0001
	CWH forest	-0.81	0.04	<0.0001
	ESSF forest	-0.25	0.03	<0.0001
	IDF forest	-1.88	0.07	<0.0001
	SBPS forest	-1.53	0.12	<0.0001
	MH forest	-0.62	0.04	<0.0001
	MS forest	-0.69	0.05	<0.0001
	Grass	-0.93	0.11	<0.0001
	Heather	-0.18	0.04	<0.0001
	Krumholtz	-0.55	0.04	<0.0001
	Rock	-0.08	0.04	0.037
	Water	-0.43	0.14	0.002
	Wetland	-0.60	0.09	<0.0001
Soil (Ref= Bedrock)	Colluvium	0.40	0.02	<0.0001
	Fluvial	-0.55	0.05	<0.0001
	Glaciofluvial	-0.94	0.05	<0.0001
	Glaciolacustrine	-1.25	0.16	<0.0001
	Lacustrine	-0.92	0.18	<0.0001
	Organic	-1.39	0.07	<0.0001
	Till	-0.41	0.02	<0.0001
Fire Age Ref = <15 Years	15-50Y"	-0.56	0.06	<0.0001
	F51-80Y	-1.01	0.09	<0.0001
	>80Y	-1.10	0.05	<0.0001
Forest Harvest Age Ref= <11 years	11-30Y	0.04	0.07	0.57
	31-50Y	-0.10	0.08	0.22
	>50Y	0.11	0.07	0.11

Table A3-3: Late summer resource selection model (August-September) developed from GPS grizzly bear locations in the southern Coast Mountains of British Columbia. Covariates are scaled for comparison.

Category	Variable	β	SE	P val
Environmental	δEVI	0.88	0.01	<0.0001
	Solar Radiation	1.03	0.01	<0.0001
	Westerliness	0.01	0.01	0.03
	Slope	0.27	0.01	<0.0001
	Canopy closure	-0.32	0.01	<0.0001
	Whitebark pine cover	0.20	0.01	<0.0001
Climate	Degree Days <0°C	-0.47	0.02	<0.0001
	Winter precipitation as snow	0.76	0.01	<0.0001
Landscape Cover (Ref= Alpine Herb)	Anthropogenic	-0.68	0.18	0.001
	Avalanche chutes	-0.26	0.04	<0.0001
	Shrub-Avalanche Chute	-0.48	0.04	<0.0001
	CWH forest	-1.12	0.04	<0.0001
	ESSF forest	-0.33	0.03	<0.0001
	IDF forest	-0.81	0.06	<0.0001
	SBPS forest	-0.99	0.09	<0.0001
	MH forest	-0.14	0.03	<0.0001
	MS forest	-1.57	0.05	<0.0001
	Grass	-1.69	0.12	<0.0001
	Heather	-0.35	0.03	<0.0001
	Krumholtz	-0.50	0.03	<0.0001
	Rock	-1.44	0.03	<0.0001
	Water	-1.84	0.11	<0.0001
	Wetland	-1.36	0.09	<0.0001
Soil (Ref= Bedrock)	Colluvium	0.65	0.02	<0.0001
	Fluvial	0.10	0.05	0.027
	Glaciofluvial	0.06	0.05	0.258
	Glaciolacustrine	0.35	0.11	0.002
	Lacustrine	0.09	0.17	0.610
	Organic	-0.23	0.06	<0.0001
	Till	0.74	0.02	<0.0001
Fire Age Ref = <15 Years	15-50Y"	1.79	0.07	<0.0001
	F51-80Y	0.46	0.11	<0.0001
	>80Y	0.01	0.07	0.849
Forest Harvest Age Ref= <11 years	11-30Y	1.78	0.07	<0.0001
	31-50Y	0.02	0.08	0.843
	>50Y	0.03	0.07	0.679

Appendix 2: Spatial Outputs Summary

Geodatabase includes core habitat areas, resistance layers, cost weighted distance files each describing attributes of connectivity between core habitat areas including connectivity across current population fractures.

SWBC_linkage.gdb

Sub-file name	**Type**	**Description**
CORE	Polygon feature	Core habitat areas for spring and later summer.
Current_50cut	Raster	Current flow identifying potential pinch points in connectivity. Cut for display purposes.
Corridors	Raster	Cumulative least-cost corridors.
Current_adjacentPairs_50K	Raster	Current flow identifying potential pinch points in connectivity.
LPCs	Line feature	Least-cost paths between core areas.
CWD	Raster	Cost-weighted distance path. The least accumulative cost required to move between a cell and a specified source. Good for identifying barrier effects.
Resistance	Raster	Cumulative resistance. Amalgamation of inverse habitat selection and building density.

Appendix 3: Additional Connectivity Maps

Downton and Carpenter Reservoirs

There is genetic evidence of population isolation between the McGillvary Mountains portion of the South Chilcotin population between the Downton and Carpenter Reservoirs and Seton and Anderson Lakes to the south (Apps et al. 2016). Both reservoirs appear to form a barrier to movement in the region and of the 12 females collared in the area only one young female crossed this area by swimming across the Downton Reservoir (FigureA3-1). Another Male bear frequently used the area between the lakes in and around the community of Gold Bridge. This bear was eventually killed due to conflict with humans. Connectivity between the lakes is currently mostly intact and the confluence of the Hurley and Bridge Rivers provides a natural link between populations, however the proximity to permanent human settlement highlights the importance of ongoing attractant management and community engagement (GRANTS ONE).

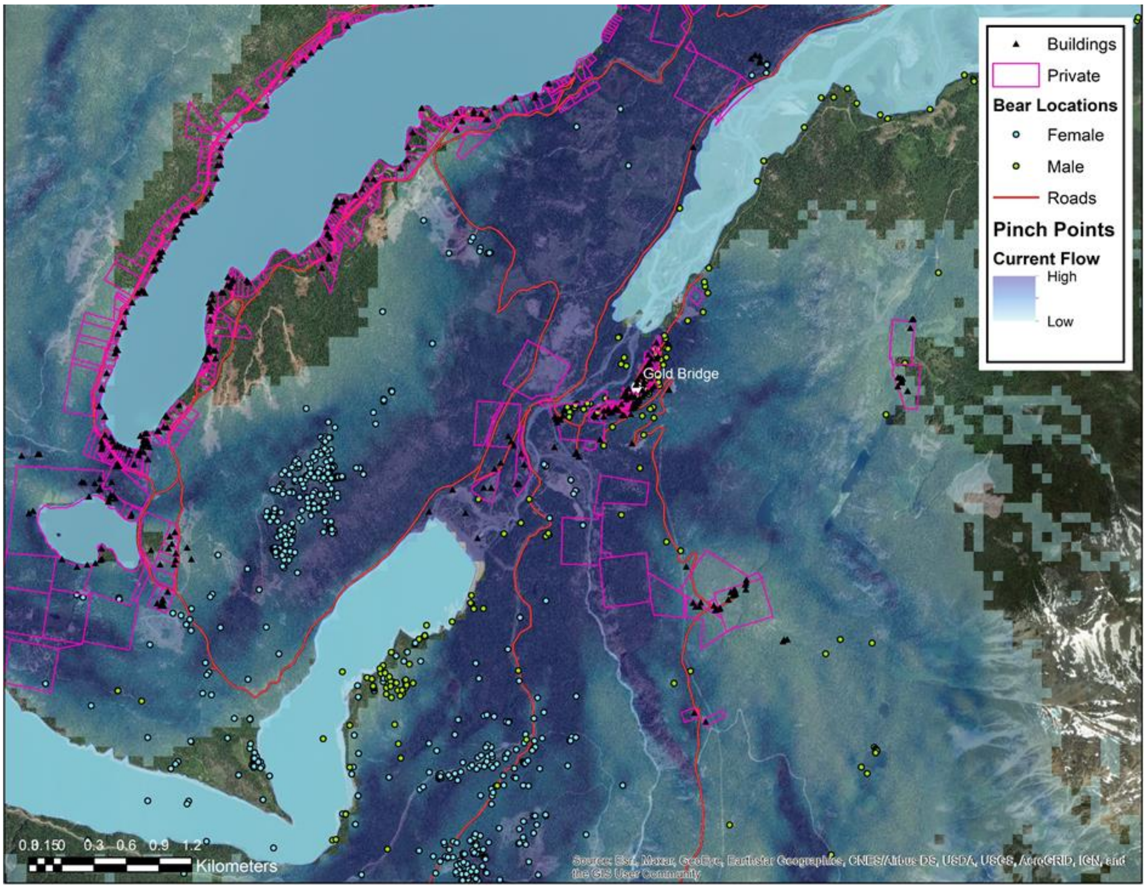

Figure A3-21: Connectivity pinch point between Downton Reservoir (right) and Carpenter Reservoir (left). Large lakes were defined as geographic barriers to movement and connectivity between the north and southern parts of the South Chilcotin population unit may be funnelled between the reservoirs near the town of Gold Bridge. However, bears swam across the reservoir where it was <600m across indicating that movement across the reservoirs is possible, and maybe preferred by some bears.

Seton Lake and Lillooet

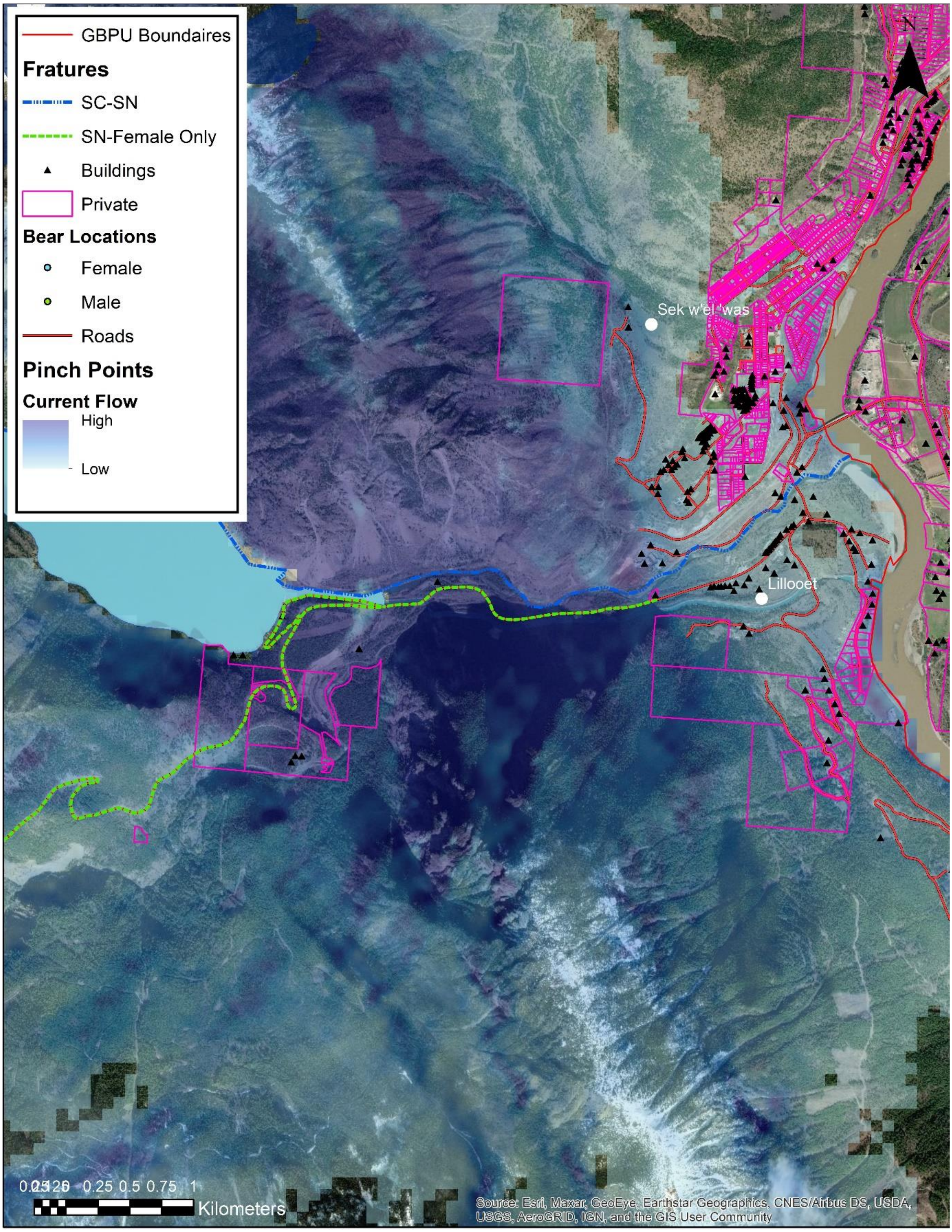

Figure A3-22: Inter population connectivity between the South Chilcotin and Stein-Nahatlatch populations between Seton Lake and the town of Lillooet.

Anderson and Seton Lakes

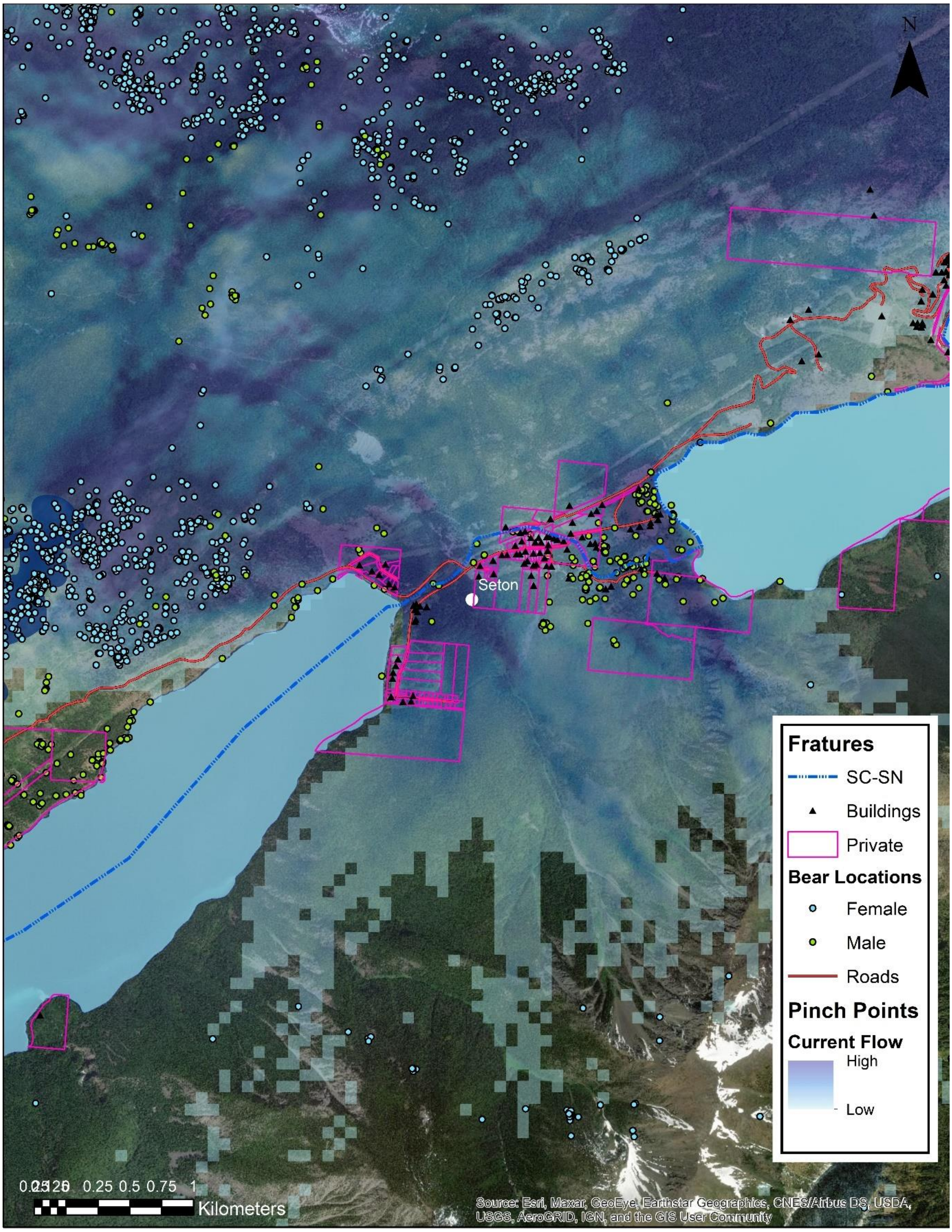

Figure A3-23: Inter population connectivity between the South Chilcotin and Stein-Nahatlatch populations between Anderson and Seton Lakes and the communities of Seton and Shalalth.

Anderson Lake-D’Arcy/N’Quatqua

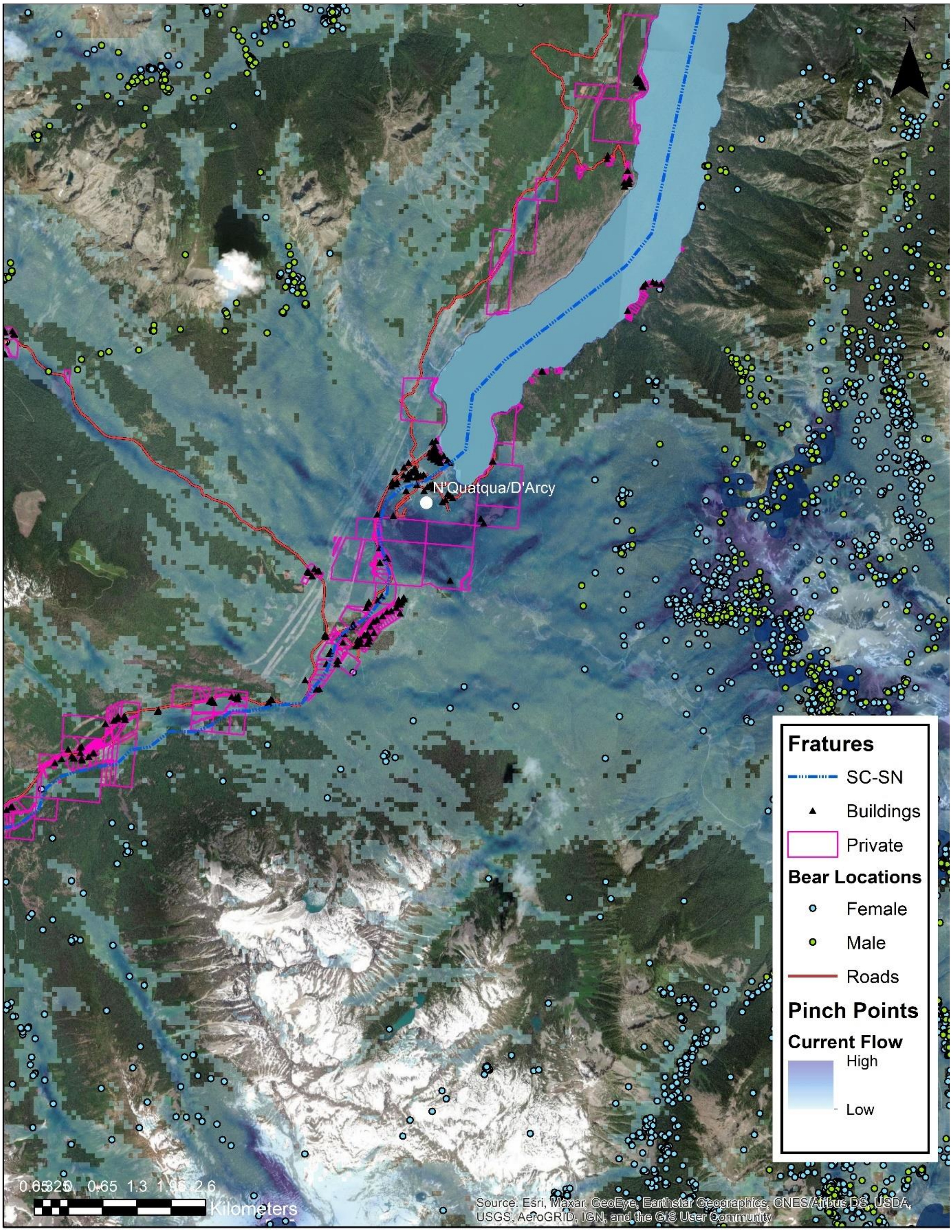

Figure A3-24: Inter population connectivity between the South Chilcotin and Stein-Nahatlatch populations at the west end of Anderson and near the communities of D’Arcy and N’Quatqua.