Habitat Connectivity Mapping between the Stein-Nahatlatch and South Chilcotin Grizzly Bear Populations

Michelle McLellan

Southwest BC Grizzly Bear Study

May 2018

Prepared for

Coast to Cascades Grizzly Bear Initiative

Nature Conservancy of Canada

Pemberton Wildlife Association

FOR MORE INFORMATION CONTACT:

Michelle McLellan

4667 Carlson Rd.

Nelson BC V1L 6X3

SUGGESTED CITATION:

McLellan, M. L. 2018. Habitat Connectivity Mapping between the Stein-Nahatlatch and Southern Chilcotin Grizzly Bear Populations. Conservation Northwest.

OBJECTIVE

The objective of this analysis is to identify which are areas of suitable grizzly bear habitat within the current population fracture between the South Chilcotin and Stein-Nahatlatch grizzly bear populations in southwestern British Columbia. The conservation of these linkage zones will maintain habitat connectivity and hopefully increase genetic connectivity between the two populations.

INTRODUCITON

Population fragmentation is a well-documented threat to wildlife species all over the world. Following fragmentation, the smaller, isolated populations are at a much-increased risk of extinction because of behavioural, genetic, or demographic Allee effects, and simply because of a declining ratio between the remaining suitable habitat and the unfavourable conditions along the edge of their distribution. Extirpation of small, isolated populations is the typical pattern of range reduction and in some cases, population extinction.

Across a species distribution, habitat quality varies enormously often patches or broad areas of high quality core habitat separated by marginal or poor habitat. Population fragmentation occurs when the movement of individuals between core habitats is restricted. Restriction is commonly due to increased mortality or a decline in habitat quality between core habitat thus decreasing the likelihood that these areas will be used by individuals or that they will be selected for by dispersing individuals.

Linkage zones are usually smaller areas of suitable habitat connecting much larger areas of core habitat. In fragmented landscapes, maintaining linkage between populations will increase the likelihood of population persistence by allowing genetic and demographic rescue to portions of the population that are small and face additional threats to their persistence.

Although grizzly bear distribution in North America is expansive, the southern edge is contracted into two narrowing peninsulas of occupancy that both end in isolated populations of varying sizes[1,2]. The western peninsula extends along the Coast Mountain ranges of British Columbia (BC) ending in five populations considered by the BC provincial government to be Threatened[3]. Population surveys in 2004-2007 obtained by large-scale DNA mark recapture methods that spanned the region identified major geographic and genetic fractures as well as large differences in grizzly bear density among some of these populations [4]. Specifically, two populations may have been recently extirpated and three more, mostly isolated populations, are considered “Endangered” by the IUCN [5]. More recently, an 8 year DNA mark recapture based monitoring program in two of the threatened populations showed that the population in the southern portion of the South Chilcotin grizzly bear population unit (GBPU) was growing but the population in the Stein-Nahatlatch GBPU, was likely in decline (Figure 1)[6]. Low genetic heterozygosity indicates that the Stein-Nahatlatch population has been isolated; indeed only two male bears genetically tagged in the 16 year span of population monitoring had crossed the population fracture and reproduced [4,6].

The future of the Stein-Nahatlatch grizzly bear population is perilous. A low density of ~6 bears/1000 km^2, small population size of a maximum of 23 bears, plus low genetic variability or heterozygosity indicates that this population is vulnerable to extinction[6]. Connectivity with the growing South Chilcotin population to the north is critical for the Stein-Nahatlatch population's long-term persistence via genetic and demographic rescue.

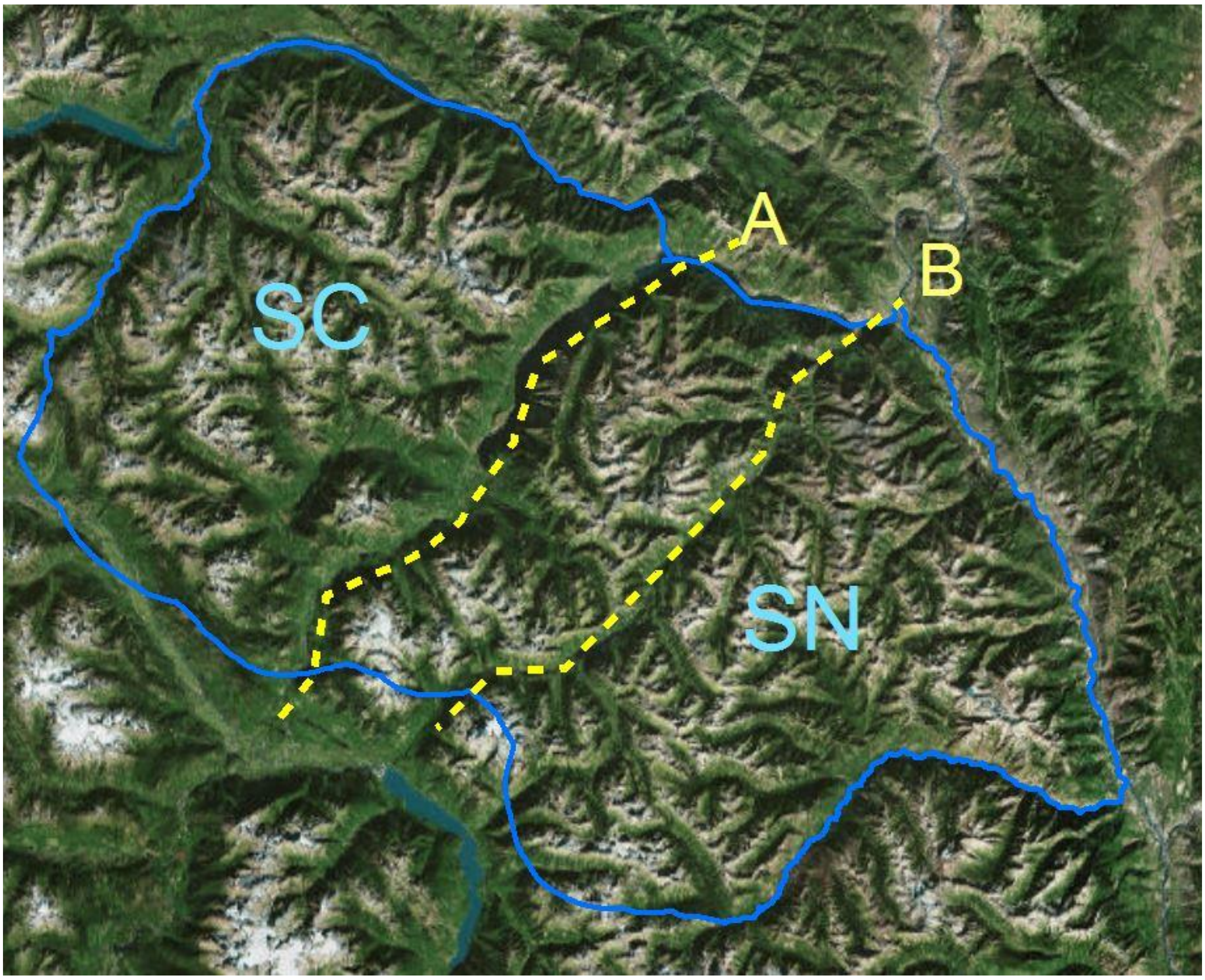

Figure 1: The study area includes the southern portion of the South Chilcotin grizzly bear population (SC) and the northern portion of the Stein-Nahatlatch (SN). Population fracture A is infrequently crossed by grizzly bears and is the boundary between the two populations. Fracture B is crossed by male bears but no female (excluding translocated bears) bears have been documented to cross. It is within the SN population unit.

Here I used elements of least-cost path analysis and circuit theory to estimate connectivity corridors and specific linkage zones within and between the South Chilcotin and Stein-Nahatlatch grizzly bear populations. Least cost-path analysis involves the estimation and amalgamation of the best routes connecting core habitats based on the resistance due to habitat quality and mortality risk[7]. Cumulative least-cost path analysis is valuable for identifying areas of intact and fragmented habitats and the best pathways through fragmented habitats. When the principles and mathematics of circuit theory are applied to core and resistance spatial data, the likelihood that a bear will travel through a certain area is analogous to current flow[8]. When there is little resistance to flow in all directions, such as within core habitat or across habitats with little resistance, the concentration of current flow is low and spread out. But in areas with patches of high resistance, current is concentrated into smaller linkage areas. Linkage areas within intact landscapes are important for the maintenance of population stability. In fragmented landscapes, linkage areas are often pinch-points in connectivity between core habitats and are vital for to interpopulation connectivity by allowing for dispersal and geneflow between populations. Other researchers have successfully applied circuit theory to identify potential and realized linkage zones between five largely isolated grizzly bear populations along the Canada US border in the Selkirk and Purcell mountains [9].

In this analysis, resistance to grizzly bear movement across the landscape was based on habitat quality and increased risk of mortality as a function of building density. Using GPS telemetry locations of grizzly bears from both populations I developed a resource selection function (RSF) to model habitat quality across the study area. A RSF relates habitat use by grizzly bears to availability based on a variety of habitat covariates[10,11] and can then be used to model the relative probability that a bear will use or select any specific area. The inverse of selection can be thought of as a resistance to movement where bears are less likely to use an area with little or no landscape attributes normally selected by individuals. Large continuous areas of high quality habitat were delineated as core habitat areas between which connectivity could be assessed.

In the autumn of 2015, an 8-year-old female grizzly bear that had never had cubs was translocated from the South Chilcotin population to the Stein-Nahatlatch population in effort to increase population size and genetic diversity of the population there. Although after one full year she returned to her natural home range, her movements through an unknown landscape are a case study of the efficacy of the linkage and connectivity models for predicting the navigation of a disperser through the landscape.

Study Area

The study area is located in the eastern portion of the Coast Mountain Range approximately 160 km North of Vancouver, BC. The area is rugged, with elevations ranging from 240m to 2,920 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 dry and low elevation forests are dominated by interior Douglas fir (*Pseudotsuga menziesii*). In the transition between wet and dryer forests there are a few 10 to 20-hectare patches of whitebark pine (*Pinus albicaulis*) dominated subalpine parkland. Due to high snowfall and rugged mountains, avalanche chutes are common throughout most of the study 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.

The grizzly bear populations are divided by several small communities along Pemberton-Portage road from Mount Currie to D'Arcy and by Seton village 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 southern boundary of the study area is the Stein River located in the centre of a large (1,300 km^2), un-roaded protected area. The northern boundary of the study area is Carpenter Reservoir and the Hurley river. A paved highway parallels the Carpenter Reservoir to Goldbridge and receives approximately 200 vehicles/day in summer (2011) while a gravel forest service road parallels the Hurley river and drops down to the upper Lillooet river and Pemberton meadows this receives approximately 100 vehicles/day (2011) and is open only in summer months. This road is crossed regularly by both female and male bears.

METHODS

Capture and Collaring

Between 2005 and 2016 we captured and fit 34 (22 female and 12 male) grizzly bears with GPS telemetry collars that provided 116,671 verified locations. Except for two adult males, all grizzlies were immobilized from a helicopter using a combination of tiletamine and zolazepam (Telazol®) administered with a projectile. Collars were programmed to obtain either 8 or 24 locations per day. The bears were monitored until their collar batteries died or the collar dropped. All collars were fit with a canvass spacer that rotted off so that the collar was guaranteed to fall off even if it malfunctioned.

Habitat Modelling

Using the GPS collared bear locations, I developed a resource selection function (RSF) to estimate habitat selection and delineate core habitat areas. 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 [11]. Because the goal was to predict movement corridors throughout the study area, all habitats within the study area boundaries except for water were deemed to be available to the bear populations. The number of locations necessary to accurately estimate availability is specific to the combination and degree of autocorrelation of the habitat variables used in an analysis, the heterogeneity of the variables in a landscape, and the size of the area for which we want to estimate availability[12]. For this study area, I estimated the resources available to the bears from 98,500 randomly located points within the study area boundary.

To avoid bear specific bias I randomly selected a maximum of 2500 locations from each bear that had more[9]. If a bear was not collared for an entire season, then the locations from that bear and season were excluded to avoid seasonal bias. For a detailed description of the bear seasons for the two populations considered here see McLellan and McLellan, 2015. Finally, only bear locations obtained between morning and evening civil twilight were included to target habitats selected for feeding and moving as opposed to night when bears are usually asleep[13].

Model building followed the methods described in Proctor et al. 2015. First, predictor variables were tested for multicollinearity which can decrease the precision of the model and possibly create erroneous results[14]; if two predictor variables had a Pearson correlation coefficient of >0.6 [15] they were not included in the same model for subsequent model selection. For each remaining predictor variable, I conducted a univariate logistic regression to estimate the explanatory power of each variable using McFadden's pseudo-R^2 statistic. Multivariate logistic regressions were built by adding each variable from high to low in order of their individual pseudo-R^2 value. If the inclusion of a variable increased model performance by >5% or it's exclusion changed the β parameter by more than 20%, it was retained in the final model[16]. 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.3.4.0)[17] using lme4 (V.1.1-14), pscl (V.1.5.2) and MASS (7.3-49) packages.

Model performance was tested using repeated k-fold cross validation[18]. 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. I also calculated the receiver operating characteristic curve (ROC) and K-fold Kappa accuracy estimates for each of 5 folds. These are model fit statistics that will be biased low for use-availability data but because the data set is large, the statistics are useful for understanding the accuracy of the fit model. ROC and Kappa accuracy estimates were obtained using pROC (V.1.11.0) and caret (V. 6.0-70) packages respectively. K-fold estimate function was developed in R.

Environmental Variables

Environmental covariates used to develop habitat models could be categorized into five types: landscape cover, whitebark pine cover, disturbance history, abiotic ecological factors and human road use. Landscape cover was defined 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 [19]. 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 as described in the VRI. Forest types in the study area included coastal western hemlock (CWH), Engelmann spruce and sub-alpine fir (ESSF), interior Douglas fir (IDF), mountain hemlock (MH), montane spruce (MS), and ponderosa pine (PP). The latter sometimes mixed with open dry grasslands.

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 of alpine scale was developed by examining the relative greenness in areas that had been visited by researchers and where vegetation plots had been recorded (see McLellan 2007). 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 [19]. 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 consisted of two binary variables indicating whether a polygon had been subject to either fire or logging. Only forests harvested since 1970 were included because sites older than 40 years had mostly regenerated to have many ecological attributes and species of a forest. Fires newer than 1955 were included because older fires were difficult to delineate from neighbouring undisturbed forest.

Several ecological variables shown in other research to be useful indicators of grizzly bear habitat were included[9,20,21]. A digital elevation model with 30 X 30 m resolution; [22,23] was used to derive elevation, slope, aspect, solar radiation, compound topographic index (CTI) as a surrogate for terrain wetnesss[24], terrain ruggedness index[25]. 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. Greeness is an index of vegetative productivity, derived using a tassled cap transformation using imagery collected from Landsat 8 satellite on 29 July 2014 when there was <3% cloud cover [26,27].

Roads layers were obtained by amalgamating digital road layers from the provincial database, Ainsworth Forest Company and manually digitizing otherwise new roads. Overgrown or reclaimed roads that were no longer travelable by vehicle were removed. Traffic counters were placed on many of the road segments in the study area. Traffic was also measured by counting vehicles per time period while travelling on the road network. The traffic counters collected time stamped data so I adjusted for daytime bias of road segments. Roads fell into three categories according to traffic volume, high (≥ 100 vehicles/day), medium (20 -100 vehicles/day) and low (≤ 20 vehicles/day). These traffic volume bins matched bins measured by others estimating grizzly response to roads[28].

For each traffic volume category, I created a Euclidean distance matrix to extrapolate the distance from each location to the nearest road. Roads within towns and settlements were excluded so that we could measure separate effects of roads and human residences or towns by eliminating the portions of roads that are correlated to the town. Distance variables were transformed to exponential decays ranging in the form of $1-(e^{-\alpha d})$ where d was the distance in km and α was set to 0.002 [15] making effects of roads irrelevant at large distances (>1.5km). The resulting value is 0 at the road and 1 at very large distances. All data was organized and overlaid in a geographic information system (ArcMap V.10.4).

Identification of Core Areas

The resource selection function was used to produce predictive maps of the relative probability of occurrence across the study area[11,29]. Areas, in this case 30x30 m pixels, where the proportion ratio of use to availability is >1 are what the model predicts to be selected habitat types.

Core habitat areas were delineated from amalgamated clusters of cells above the selection threshold > 2.3 km^2 which is the average daily home range size of female grizzlies in this study area.

Linkage analysis and Connectivity Mapping

I used two methods to identify linkage areas between core habitat areas: 1. cumulative least-cost corridors, and 2. potential movement pathways which are estimated using the principles of circuit theory. In their application both methods use the cost-weighted distance from each core area estimated across the surface of the study area.[7] The cost-weighted distance is the accumulated cost of moving away from a core habitat, which depends on both the distance from the core habitat and the resistance to moving through each patch of habitat or cell. In this analysis, the resistance to travelling through each cell was the equally weighted combination of the inverse RSF value for that cell and the building density around the cell centre. Building density was used as a surrogate for mortality risk because humans are the most common cause of adult grizzly mortality in many populations, especially for unhunted populations that overlap with rural residential and agricultural areas [9,30–32]. I digitized buildings manually from 2015 ESRI imagery with 0.5 m resolution[33] and used a moving circular window with a radius of 500 m to estimate the building density surrounding each cell. Both resistance factors and the final resistance in each cell were scaled from 0 to 1 where 0 is resistance such as within a core habitat area and approaches 1 in habitats with a very low probability of selection or in areas with high building density.

In the first method, cumulative least-cost corridors were developed to identify intact landscapes and highlight barriers to connectivity. Cumulative least-cost corridors can be mapped across the landscape and are the combination of all pairwise least-cost corridors. The least-cost corridor between a pair of core areas is the sum of the cost-weighted distances from each, normalized by subtracting the cost of the single best pathway. The resulting raster surface becomes a measure of the cumulative cost distance ranging from 0 at the least cost path upward. The sum of all pairwise least-cost corridors is the cumulative-least cost corridors measured for each pixel across the landscape. Cumulative least-cost corridors are more likely to predict pathways 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 along one of the least-cost corridors. One caveat of this method is that because multiple cost-weighted distances are overlaid, there is the potential for creating cul-de-sacs of good habitat and not connections between core habitat areas.

Using the second method, potential movement pathways between core areas and across the study area were estimated using the principles of circuit theory. In 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 [8]. This method uses the same cost-weighted distance estimated using the same resistance layer as least-cost corridors. 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[8]. Connectivity cul-de-sacs are also less likely with this method.

Linkage analyses were conducted using the Linkage Mapper® tool[34] in ArcMap V.10.4. To model pinch-points in linkage areas I used the linkage mapper tool to run Circuitscape[35]. I limited pathways to 50 km Euclidean distance. This distance 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

The reduced data set included 35,179 daytime locations from 27 grizzly bears (20 female;7 male). Of these, 12 bears (7 female; 5 male) were captured in the Stein-Nahatlatch GBPU and 15 were captured in the South Chilcotin GBPU (13 female; 2 male).

Except for one translocated individual whose locations were not used in RSF model development, collared female grizzlies did not use the area between Highway 99 and Pemberton portage road (Figure2) nor did any cross either fracture. This is consistent with the ongoing DNA mark recapture project within this study area that did not observe any female grizzlies in this area between 2005 and 2017[4,36]. Three collared adult male grizzlies used habitats on both sides of one or both fractures discussed in this analysis and all three had Stein-Nahatlatch genetic origin. One of these was captured as an older adult in the South Chilcotin and fished for salmon in the Birkenhead River along the Portage road fracture. He used the river habitat near the Portage road fracture and around the Mount Currie townsite. Another was captured as a sub-adult and frequently crossed the Highway 99 fracture while collared and has since been genetically tagged in the DNA grid in both population units.[36] The third was an adult male that frequently crossed the Highway 99 fracture while he was collared but not the Portage road fracture. He was never genetically tagged in the South Chilcotin GBPU nor did he have any genetically tagged offspring in that population.[4,36]

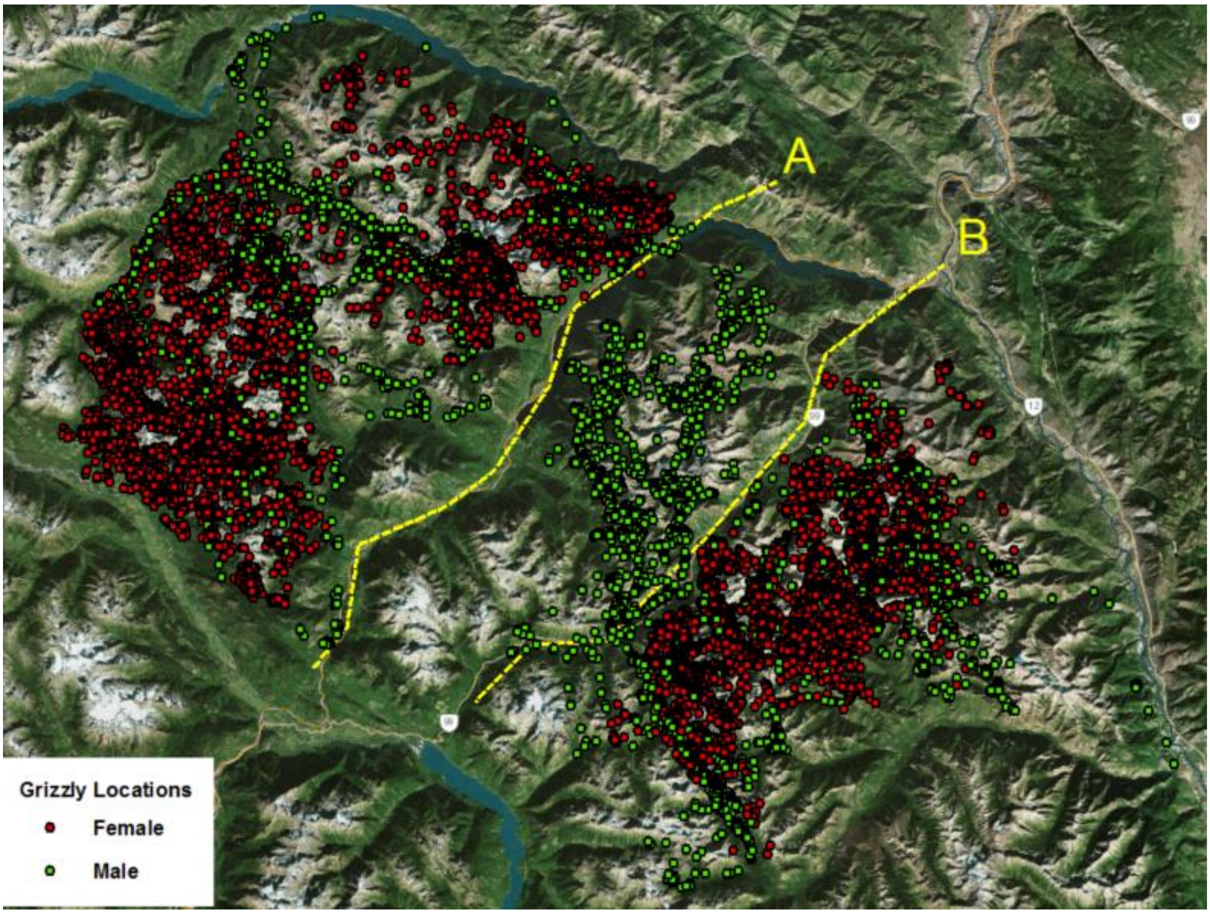

Figure 2: Daytime grizzly bear locations used for resource selection function model development.Frature A divides the South Chilcotin and Stein-Nahatlatch grizzly bear populations. Fracture B runs parallels highway 99 and the Cayoosh river. It is frequently crossed by male grizzly bears, but no female grizzlies have been known to cross it

Resource Selection Functions

The final resource selection model included landscape class, elevation, greenness, solar radiation, westerliness, slope, percent canopy cover, percent whitebark pine cover, history of logging, history of fire and the decay distance to high and low traffic volume roads (Table 1). Terrain ruggedness and southerliness were both excluded in the first step of model selection because they were highly correlated with slope and solar radiation respectively but had lower pseudo-R^2 and higher AIC. Both CTI and medium traffic volume roads were not significant predictors of bear use and did not improve model performance or affect coefficients of other predictor variables and therefore were excluded.

Most of the significant predictor variables identified in this RSF are similar to those in other studies; specifically: greenness, canopy closure, solar radiation, elevation, alpine areas, avalanche chutes and highways[9,37,38]. However, unlike some other studies, bears selected for closer distance to low traffic volume roads. Even during the day, grizzly bears will use forestry roads for travel and many high use huckleberry fields in this study area have these roads nearby. In this study grizzlies generally avoided forested areas, high canopy closure, rock, krummholz, highways and anthropogenic areas. They selected for burned and logged areas where they are known to feed on huckleberries and Saskatoon berries[39], herbaceous avalanche chutes and alpine meadows and there was a weak positive effect for areas with high cover of whitebark pine. Whitebark pine was a common food source for some bears in this study.[39]

All k-fold models were similar with mean estimated kappa accuracy of 0.834 (SEM =0.0001) when the 20% withheld locations were tested on the model created with the remaining 80% of locations. The ratio of selected habitat to availability indicated that bears selection occurred for habitat in area-adjusted RSF rank bins 9 and 10 (Appendix 2: Figure 1). The average Spearman's rank correlation coefficient was r_s=0.99 (SEM=2.16 x10^{-6}) for each repeated k-fold cross validation between predicted and area-adjusted bins for RSF scores. Finally, the area under the ROC curve was 0.8664 showing that even when some of the availability locations were likely also used by bears, the model had a fairly good predictive power.

Core Areas

The reduction of selected areas identified 17 core areas ranging from 2.3 km^2 to 11.2 km^2, 9 in the South Chilcotin part together covering 43.3 km^2 and 8 in the Stein-Nahatlatch part covering 22.8 km^2 (Figure 3).

Table 1: The final resource selection function model estimating habitat selection by grizzly bears in the Stein-Nahatlatch and South Chilcotin populations.

Category	Variable	Range	β	SE	P
Ecological Factors	Elevation	240 to 2920	4.91 x10^{-4}	4.39 x10^{-5}	< 0.001
	Green	-29825 to 19822	2.97 x10^{-4}	4.05 x10^{-6}	< 0.001
	Solar Radiation	6204 to 995332	1.27 x10^{-6}	9.82 x10^{-8}	< 0.001
	Westerliness	0 to 1	0.413	3.10E x10^{-2}	< 0.001
	Slope	0 to 90	-8.84 x10^{-3}	9.11 x10^{-4}	< 0.001
	Canopy closure	0 to 1	-7.55 x10^{-3}	7.09 x10^{-4}	< 0.001
	Whitebark pine cover	0 to 1	7.17 x10^{-3}	6.76 x10^{-4}	< 0.001
Distance to Road	High traffic	0 to 1	2.67	0.2.61	< 0.001
	Low traffic	0 to 1	-1.05	0.0438	< 0.001
Disturbance Factors	Fire	0 or 1	1.90	0.0395	< 0.001
	Logging	0 or 1	0.517	0.0396	< 0.001
Landscape Class	*Ref = Alpine herbaceous meadow*				
	Anthropogenic	0 or 1	-0.373	0.217	0.0857
	IDF forest	0 or 1	-1.72	0.0718	< 0.001
	CWH forest	0 or 1	-0.683	0.0656	< 0.001
	ESSF forest	0 or 1	-0.212	0.0464	< 0.001
	PP forest	0 or 1	-2.78	0.584	< 0.001
	MH forest	0 or 1	-0.411	0.08.05	< 0.001
	MS forest	0 or 1	-0.915	0.06.26	< 0.001
	Alpine heather	0 or 1	-0.676	0.054	< 0.001
	Herb avalanche chute	0 or 1	0.570	0.0428	< 0.001
	Shrub avalanche chute	0 or 1	-0.563	0.0650	< 0.001
	Ice	0 or 1	-0.585	0.0457	0.201
	Rock	0 or 1	-0.591	0.0456	< 0.001
	Krummholz	0 or 1	-0.808	0.0492	< 0.001
	Wetland	0 or 1	-0.130	0.135	0.3358

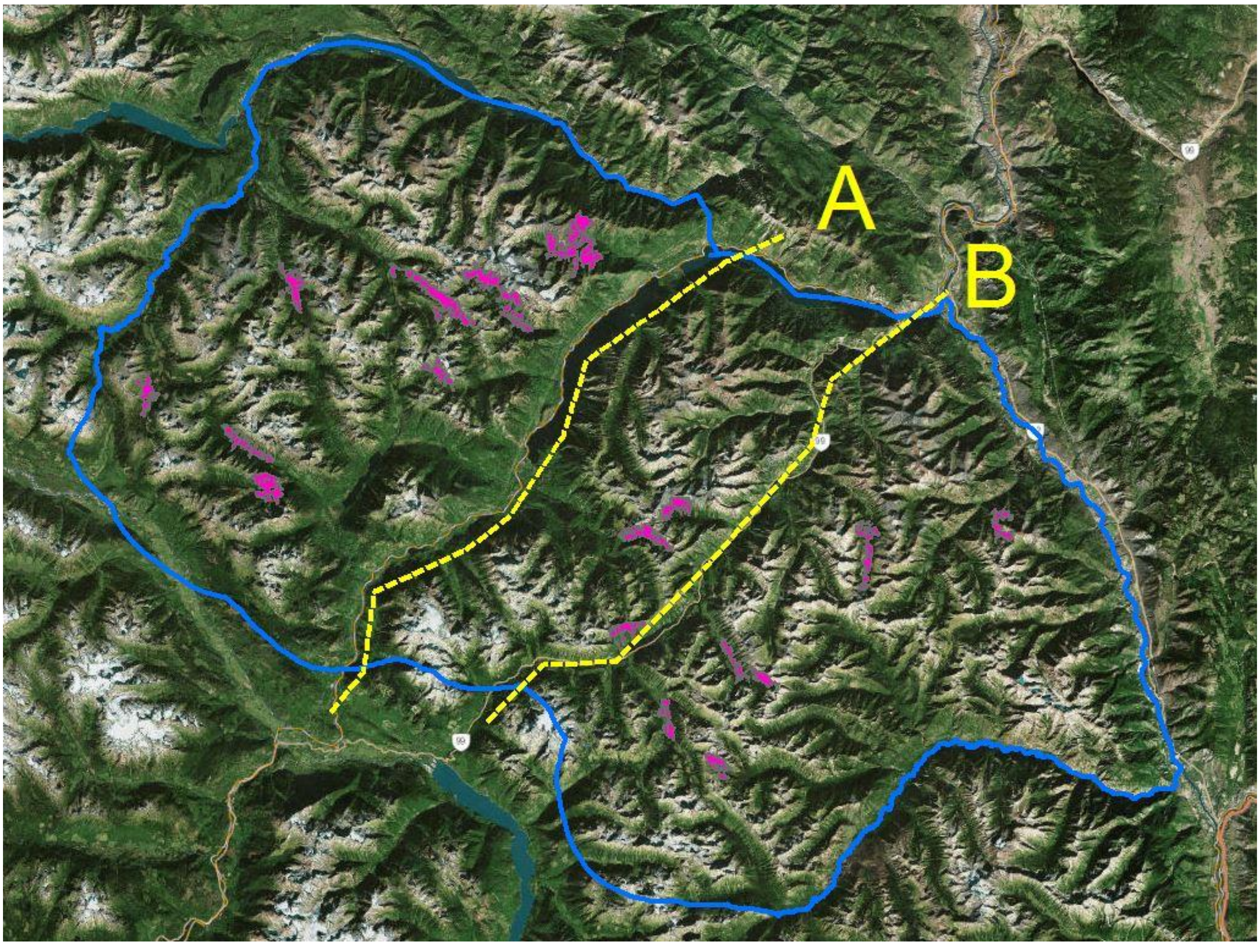

Figure 3: Core habitat for grizzly bears (pink polygons) identified using an RSF. Yellow dashed lines are the current full or partial grizzly bear population fractures. Blue line outlines the study area. Core value habitat may exist outside of these boundaries but was not identified with this model.

Linkage Areas

Within the study area I used the cumulative resistance layer including both building density and the inverse of the RSF as a habitat-based restriction to movement to identify cumulative least-cost corridors between core habitat areas (Figure 4). Both populations have very large areas with high linkage within them but corridor value decrease to the east and north in the dry Douglas fir and ponderosa pine forests and connectivity was limited by Anderson and Seaton Lakes (Figures 4 & 5). Grizzly bears seldom cross the population fracture that runs between Lillooet and the Mount Currie townsite along Seton and Anderson Lakes then along Portage road (Fracture A). Only 3 males have been documented to cross or to forage in this fracture area, one of which was killed by conservation officers for entering buildings. Connectivity across this fracture is limited in most areas by high building density and lower habitat value than in the core habitat areas (Figure 4 and 5).

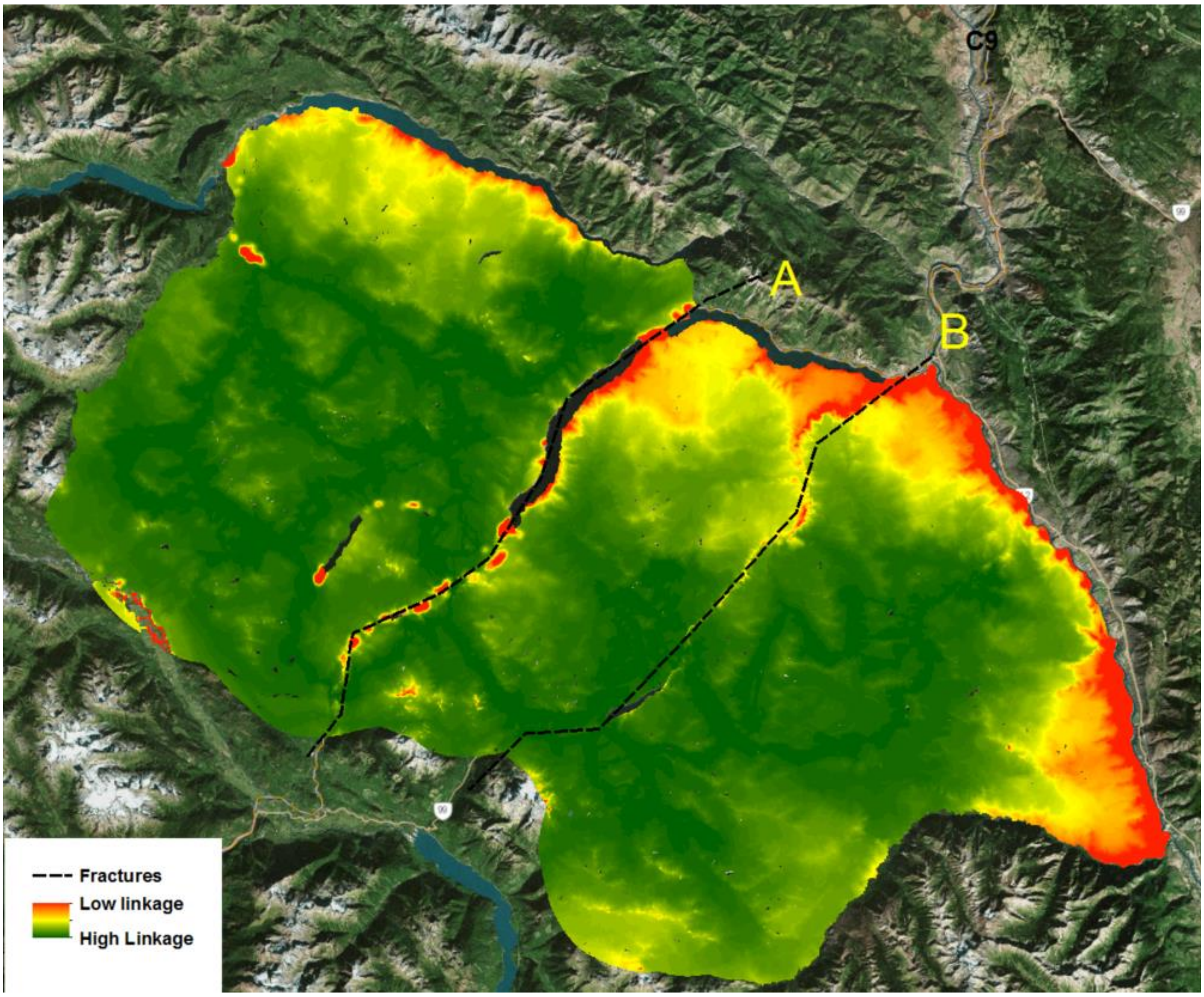

Figure 4: Cumulative least cost corridors estimated from the cumulative resistance of building density and habitat-based restrictions. The approximate location of known population and demographic fractures A and B. Fracture A follows Pemberton portage road and fracture B follows highway 99. The highway 99 fracture is regularly crossed by male grizzly bears.

Examination of the cumulative least-cost corridors through part of the population fracture A between the Stein-Nahatlatch and South Chilcotin GBPUs that runs along Pemberton Portage road shows several areas of potential connectivity. Because habitat values identified by the RSF are similar across much of the low elevation fracture area, building density is the biggest resistor to movement here (Figure 5). Nine potential connectivity areas currently exist (denoted A1-A9 in Figure 5). The least-cost paths between pairs of core areas are also the widest; A7 is ~1.6 km and A1 ~ 5.0 km and possibly wider. The same analysis done without including building density indicates likely corridor areas near A9 and A5 near the ends of the lakes. These areas, where the habitat corridor overlaps high building density, is where hazard management and efforts to reduce mortality by increasing tolerance would be best targeted.

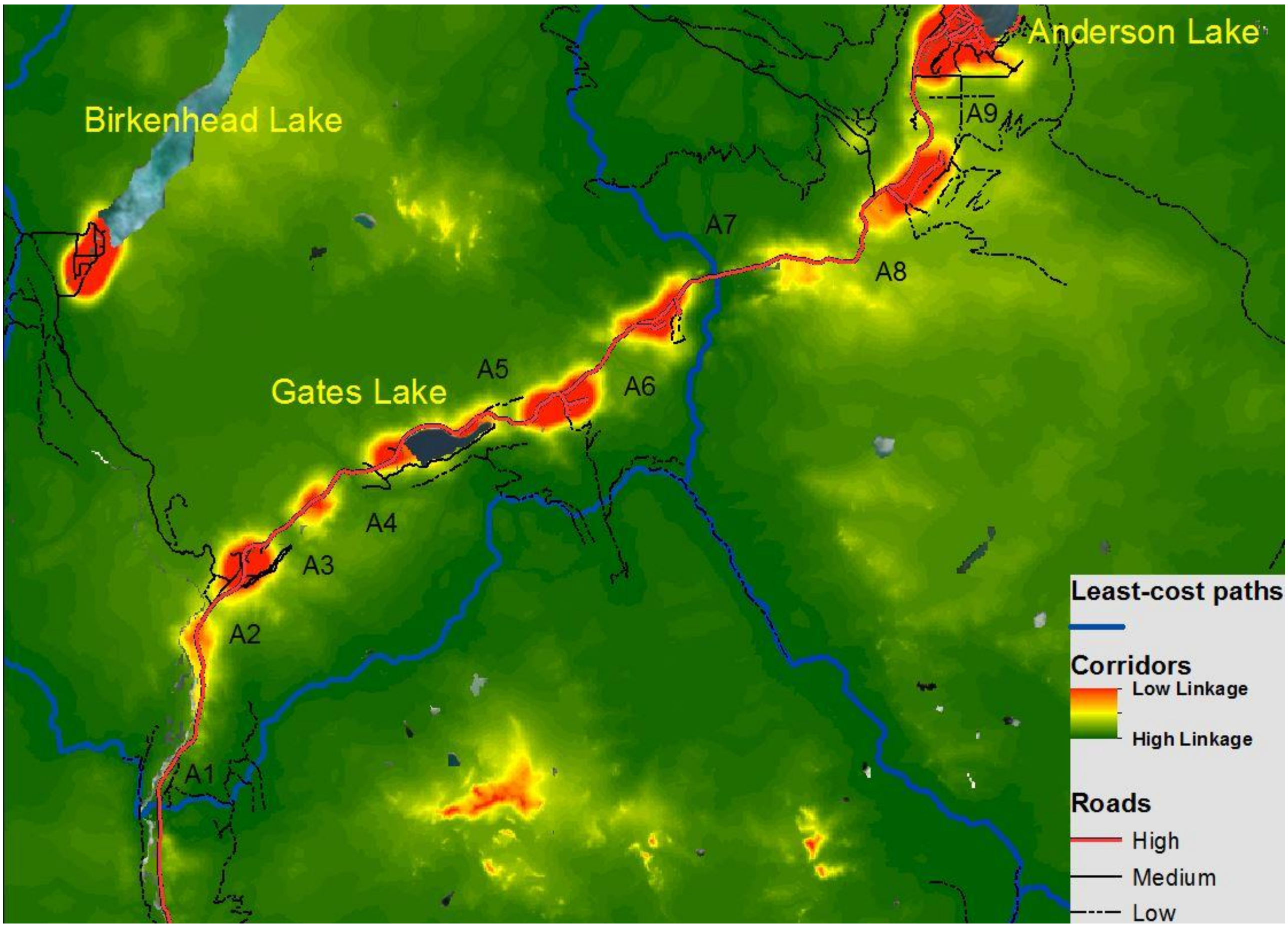

Figure 5: Identified cumulative least-cost corridors and least-cost paths for fracture A between Mount Currie and Anderson Lake/D'Arcy. A1- A9 are possible linkage areas across the facture and the least-cost paths cross at A1 and A7.

Linkage areas identified using circuit theory and pinch-point mapping identify the most probable path of a dispersing bear. These areas are therefore the most likely areas for the populations to reconnect across fractures. They have similar physical locations to the cumulative least-cost path corridors, but they highlight the ones with the most potential current flow denoting areas with increased probability of use. Linkage corridors A7 and the one south of A1 both have currents that cross both the road and rail line in fracture A (Figure 6). This method identifies the area with the highest potential within the broader A1 corridor identified in Figure 5. Linkage areas near A8 and A9 also appear to have more potential than would be predicted by cumulative least-cost corridors indicating that they may be an important linkage zone between the Stein-Nahatlatch and the more easterly core habitat areas in the South Chilcotin population.

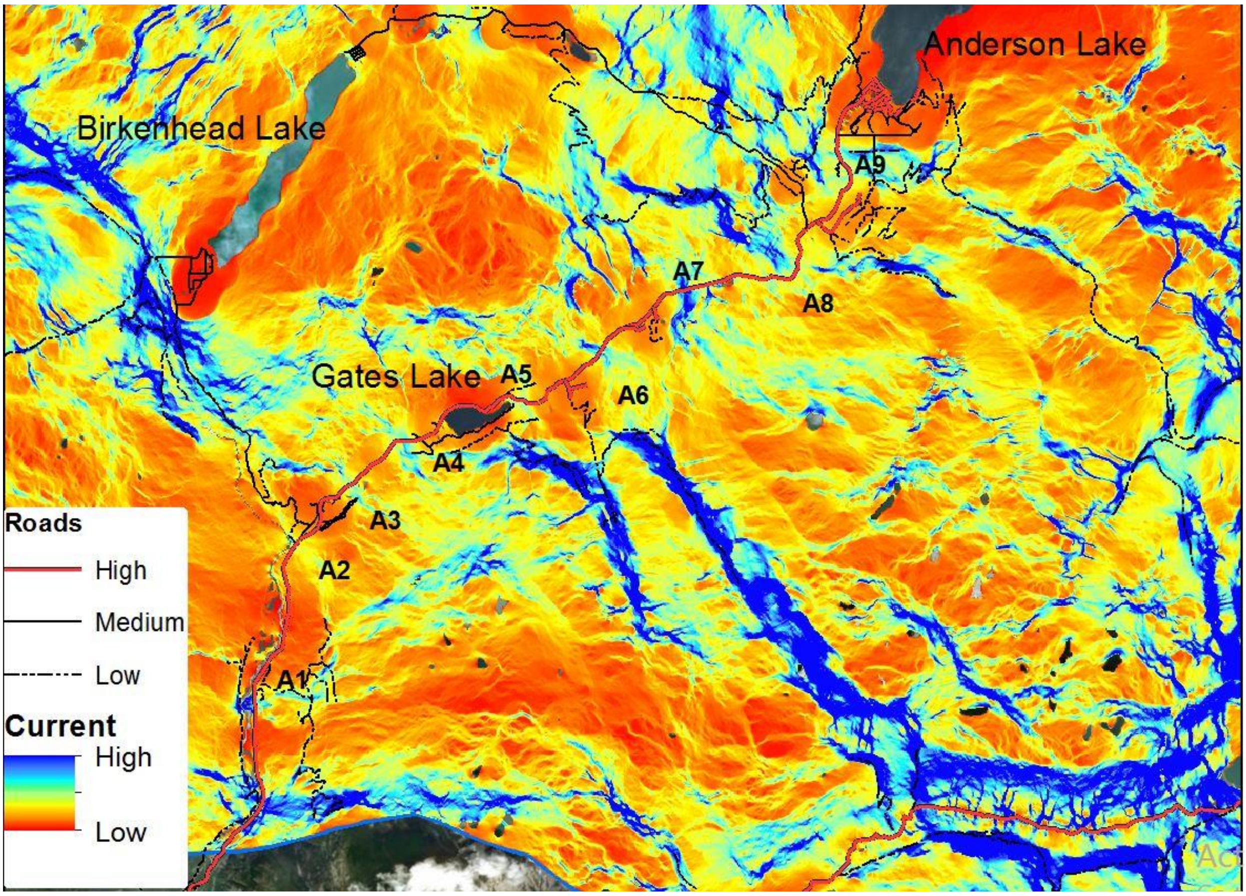

Figure 6: Current flow estimated between core habitat areas identified using circuit theory and pinch-point mapping. Current is proportional to the probability that a dispersing bear will use that path when moving across the landscape. A1-A9 are corridors identified using cumulative least-cost corridors.

The Highway 99 fracture (B) has no permanent human residences and, except for the highway, has relatively high levels of landscape integrity (Figure 7). The proximity of high quality habitats to this fracture increases the likelihood that it will be used by dispersing individuals between core areas (Figure 8). Both models identify the same areas as having high levels of landscape connectivity across the highway. The maintenance of connectivity across pinch-points B1-B3 in Figure 7 is vital to developing connectivity between the Stein-Nahatlatch and the South Chilcotin GBPUs. Efforts to protect this area from intense human use and development is imperative to the maintenance of the linkage and possible dispersal of female bears across this fracture. Current flow pinch-point mapping predicts the area between the Cayoosh pass and 7 Mile creek to the west of Mt. Marriott to be the most probable linkage corridor between the populations (Figure 6).

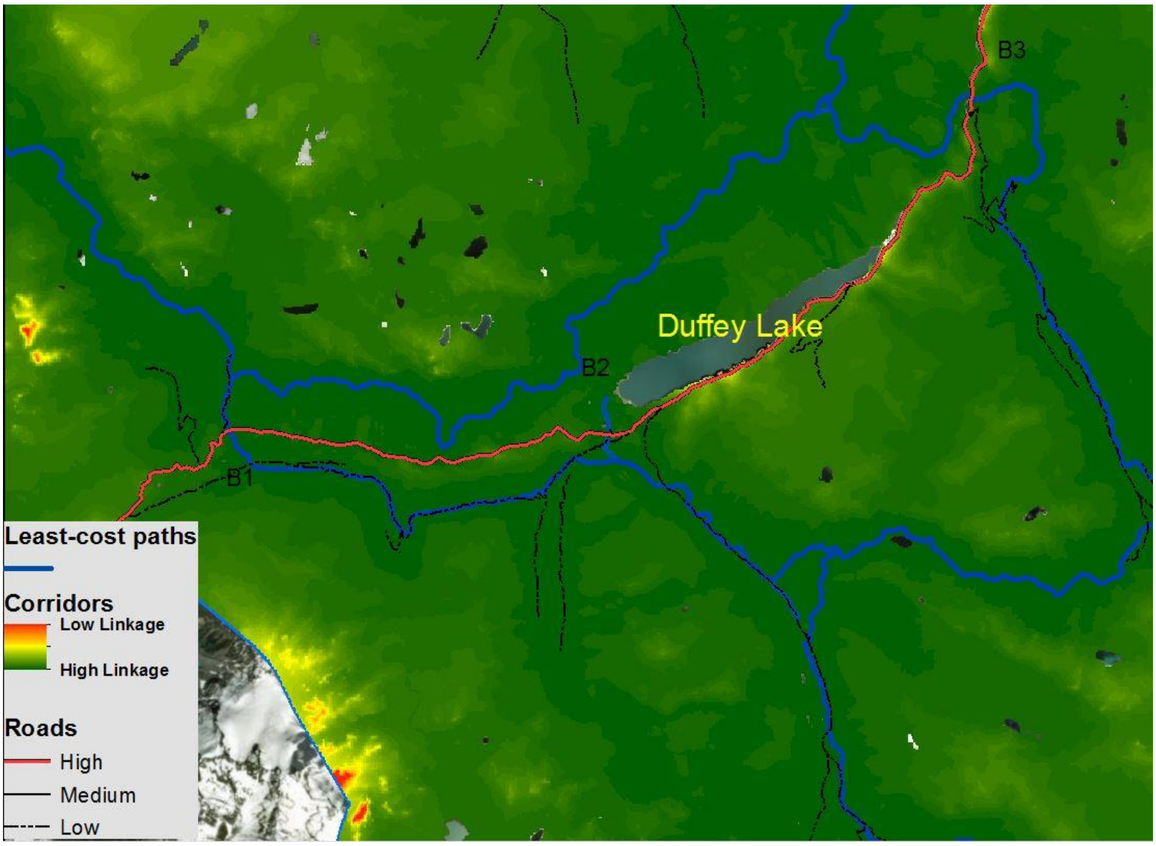

Figure 7: Identified corridors and least cost paths for fracture B along highway 99 between Mount Currie and Lillooet. Three primary linkage sites (B1-B3) crossing highway 99.

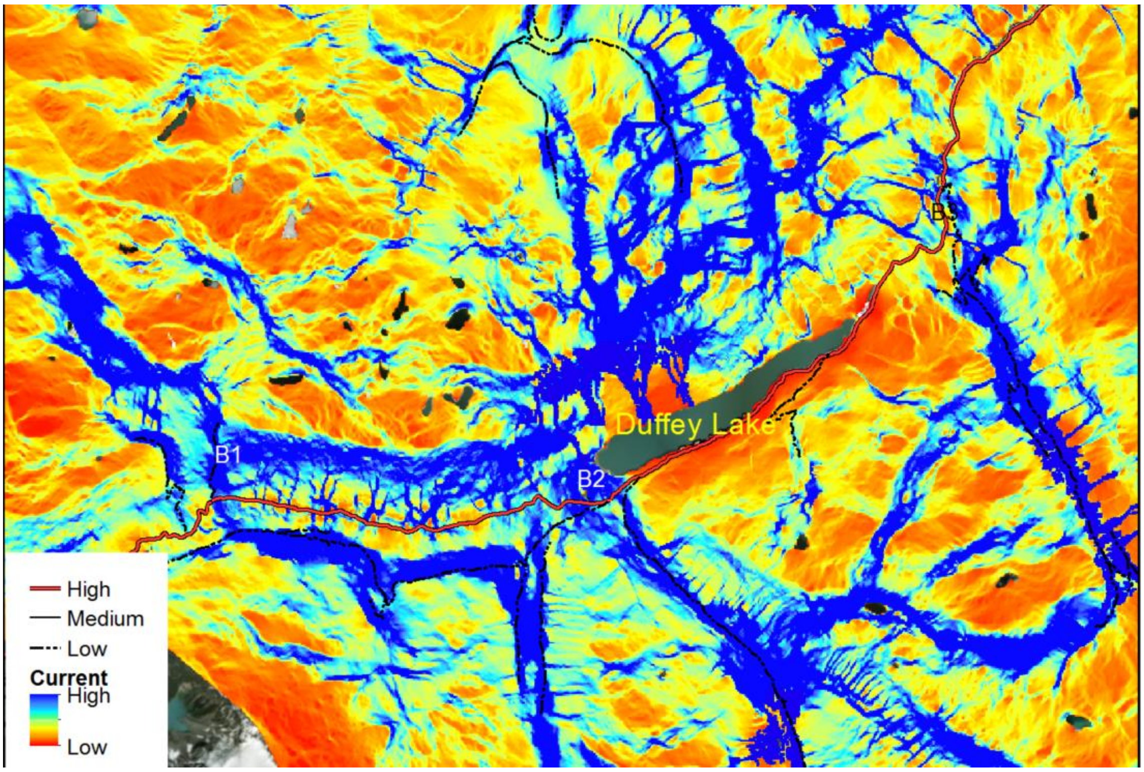

Figure 8: Current flow estimated between core habitat areas identified using circuit theory and pinch-point mapping across the Highway 99 fracture within the Stein-Nahatlatch GBPU. Current is proportional to the probability that a dispersing bear will use that path when moving across the landscape. Pinch-point linkages B1-B3 highlight important corridors for grizzly bears in this population.

Examining grizzly bear locations across this landscape shows, unsurprisingly, that most bear use is in areas with high connectivity to core areas. The movement of the translocated female returning to her natal home range in the South Chilcotin GBPU from the Stein-Nahatlatch population provided a unique experimental opportunity to test the efficacy of the connectivity models at least for one bear. Her path through unfamiliar habitat did follow areas predicted to have high current flow until she encountered the Portage Road fracture (A). She approached the fracture at multiple locations (see Figure 9 line 3) and retreated without crossing. Over the next four days (Figure 9 movement lines 4-7), she moved parallel and upslope to the fracture north eastward approaching Anderson Lake and Seton village on a few occasions (Figure 9 line 6 and 7). Then after two weeks of showing feeding like movement patterns, she denned above Anderson lake. Shortly after leaving her den in the spring, she moved back toward the fracture (lines 8 and 9) where she had come the previous fall, and then circumnavigated Mt Oleg by crossing above the Mount Currie townsite and back over to 7-mile creek. She then spent June to mid-October moving in more usual grizzly bear feeding type patterns in areas with high internal connectivity and relatively good habitat quality (Appendix 2: Figure 3). Suddenly in mid-October, she moved directly toward the fracture and crossed near A4 (Figure 10) and, after resting, continued straight back across Birkenhead lake to her home range.

Though more rigorous testing would be necessary to statistically quantify the variability of grizzly bear movements across unfamiliar terrain, additional measures are unlikely and the insights this case provides are worth considering. Her movements highlight several aspects of model accuracy and fracture permeability. First, the Highway 99 fracture was crossed immediately without apparent hesitation supporting the predictions made by both the cumulative least cost-path analysis and the current flow analysis that the landscape is relatively intact with little resistance to movement (Figure 9). Directly following the path predicted by the current flow model up to the Cayoosh headwaters and then down 7-mile creek until reaching the areas of increased resistance due to human density. Second, the limits to connectivity predicted by the cumulative least-cost corridor model (Figures 5 and 10) were significant enough to deter her for a year, and only after investigating multiple other options did she cross at a linkage zone predicted by the model.

This analysis identifies several potential linkage areas across the Portage road fracture and highlights the importance of keeping a high potential for connectivity across the Highway 99 fracture. Maintaining intact corridors and conserving linkage areas between the Stein-Nahatlatch and South Chilcotin populations is necessary for the long-term persistence of the Stein-Nahatlatch population.

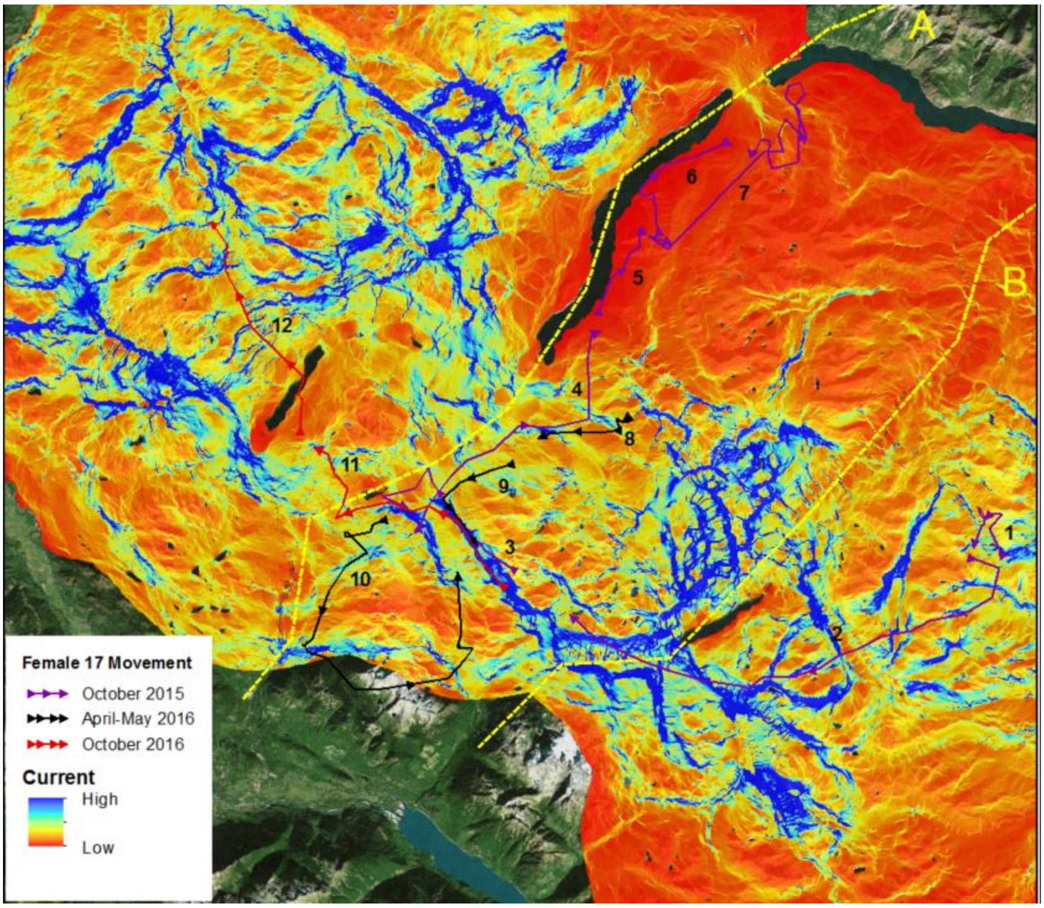

Figure 9: Lines showing the movement paths of translocated female as she returned to the South Chilcotin from the Stein-Nahatlatch population. Numbers indicate the sequence of movement segments. Each segment in October is one night of travel. Lines are superimposed on the current flow linkage model predicting the movement pathways of a bear through the landscape. Population fracture A and partial fracture B approximated with a dashed yellow line.

Potential pitfalls

Several potential pitfalls of this analysis should be considered when applying these connectivity predictions for conservation purposes. First, connectivity mapping throughout the higher elevation parts of the study area where the bears were found almost all the time is probably accurate. However, the near absence of bears in low elevation habitats will bias the RSF model's identification of habitat selection for food types found at higher elevations. This is particularly relevant to the identified corridors and linkage zones across the Portage Road fracture because it is likely that if bears used this area regularly, they may be selecting a food source that was under-represented in the RSF. Indeed, the only collared bear to use this area fished for salmon in the Birkenhead river and although he used this area constantly in the fall, the RSF does not identify this area as having higher quality habitat because he was the only collared bear that did this behaviour (and no uncollared bears were known use this area). In other parts of the study area, some grizzly bears will use lower elevation habitats in early spring for foraging on grasses and forbs when there was still abundant snow in the mountains. I expect bears to use the habitats near the fracture during early spring for the first greened up vegetation and then in fall when salmon spawn and domestic fruits ripen.

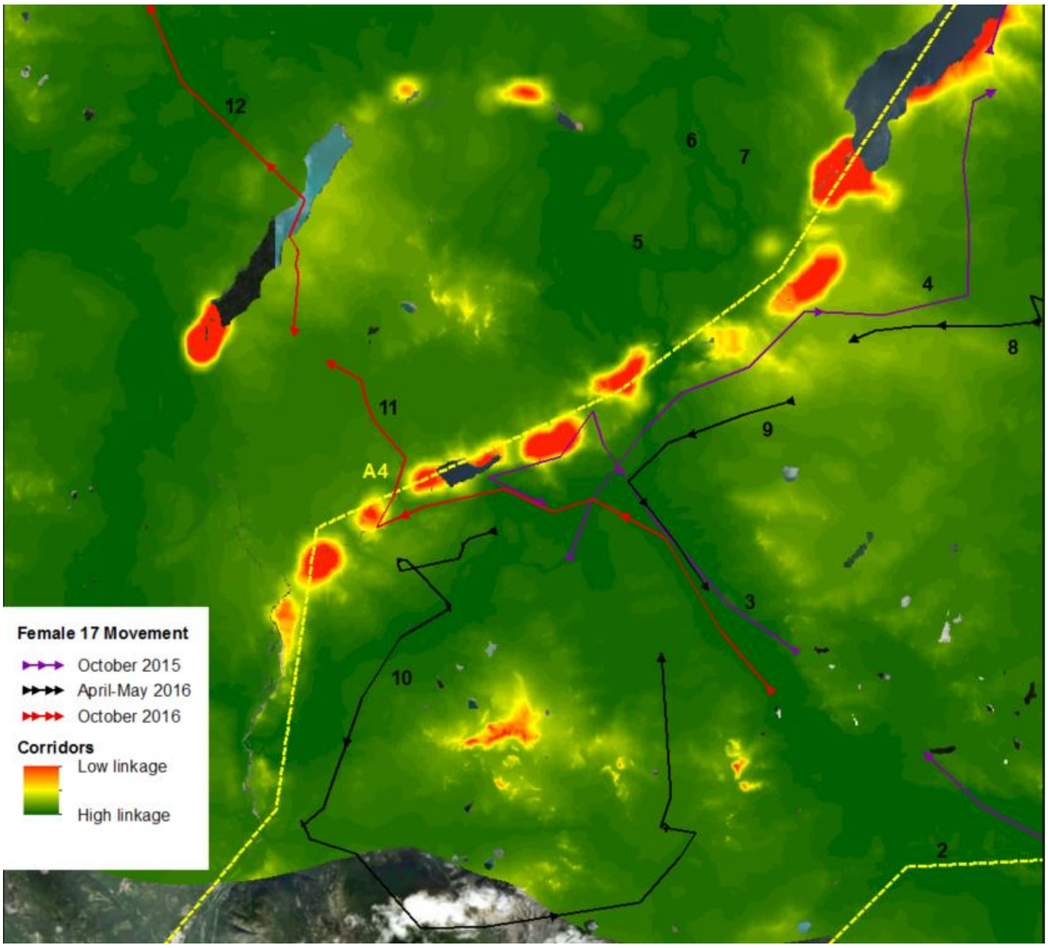

Figure 10: Lines showing the movement paths of translocated female as she returned to the South Chilcotin from the Stein-Nahatlatch population across the Portage road fracture (Yellow dashed line). Numbers indicate the sequence of movement segments. Each segment in October is one night of travel. Lines are superimposed on the cumulative least path corridors.

REFERENCES

1. Mclellan, B. N. Maintaining viability of brown bears along the southern fringe of their distribution. *Ursus* **10,** 607–611 (1998).
2. Proctor, M. F. *et al.* Population fragmentation and inter-ecosystem movements of grizzly bears in Western Canada and the Northern United States. *Wildl. Monogr.* 1–46 (2012). doi:10.1002/wmon.6
3. Grizzly Bears - Environmental Reporting BC. Available at: http://www.env.gov.bc.ca/soe/indicators/plants-and-animals/grizzly-bears.html. (Accessed: 22nd October 2017)
4. Apps, C. *et al. Grizzly bear population abundance, distribution & connectivity across british columbia's southern coast ranges*. (2014).
5. McLellan, B. N., Proctor, M. F., Huber, D. & Michel, S. The IUCN Red List of Threatened Species 2016: e.T41688A45034772. (2016).
6. McLellan, M. L., McLellan, B. N., Wittmer, H. U., Lamb, C. T. & Sollmann, R. Divergent population trends ten years after ending the legal grizzly bear hunt in southwestern British Columbia, Canada. *Biol. Conserv.*
7. Washington Wildlife Habitat Connectivity Working Group. Washington Connected Landscaptes Project: Statewide Analysis. (2010).
8. McRae, B. H., Dickson, B. G., Keitt, T. H. & Shah, V. B. Using Circuit Theory to Model Connectivity in Ecology , Evolution , and Conservation. *Ecology* **89,** 2712–2724 (2008).
9. Proctor, M. F. *et al.* Grizzly bear connectivity mapping in the Canada-United States trans-border region. *J. Wildl. Manage.* **79,** n/a-n/a (2015).
10. Johnson, D. H. The Comparison of Usage and Availability Measurements for Evaluating Resource Preference. *Ecology* **61,** 65–71 (1980).
11. Manly, B., McDonald, L., Thomas, D., McDonald, T. & Erickson, W. *Resource Selection by Animals: Statistical Design and Analysis for Field Studies.* (Springer Netherlands, 2002).
12. Northrup, J. M., Hooten, M. B., Anderson, C. R. & Wittemyer, G. Practical guidance on characterizing availability in resource selection functions under a use-availabitiy design. *Ecology* **94,** 1456–1463 (2013).
13. McLellan, M. L. & McLellan, B. N. Effect of season and high ambient temperature on activity levels and patterns of grizzly bears (Ursus arctos). *PLoS One* **10,** e0117734 (2015).
14. Graham, M. H. Confronting Multicollinearity in Ecological Multiple Regression Author (s): Michael H . Graham Published by : Wiley on behalf of the Ecological Society of America Stable URL : http://www.jstor.org/stable/3449952 REFERENCES Linked references are availabl.

Ecology **84,** 2809–2815 (2003).

15. Nielsen, S. E., Cranston, J. & Stenhouse, G. B. Identification of Priority Areas for Grizzly Bear Conservation and Recovery in Alberta , Canada. *J. Conserv. Plan.* **5,** 38–60 (2009).
16. Bursac, Z., Gauss, C. H., Williams, D. K. & Hosmer, D. W. Purposeful selection of variables in logistic regression. *Source Code Biol. Med.* **3,** 1–8 (2008).
17. Venables, W. N. & Smith, D. M. *An Introduction to R*. *R Core Team* **2.15.1,** (2012).
18. Boyce, M. S., Vernier, P. R., Nielsen, S. E. & Schmiegelow, F. K. A. Evaluating resource selection functions. *Ecol. Modell.* **157,** 281–300 (2002).
19. Ministry of Forests, L. and N. R. O. Vegetation Composite Polygons. *Government of British Columbia Data Catalogue* (2013). Available at: http://catalogue.data.gov.bc.ca/dataset/vegetation-composite-polygons.
20. Nielsen, S. E., Stenhouse, G. B. & Boyce, M. S. A habitat-based framework for grizzly bear conservation in Alberta. *Biol. Conserv.* **130,** 217–229 (2006).
21. Ciarniello, L. M., Boyce, M. S., Seip, D. R. & Heard, D. C. Grizzly bear habitat selection is scale dependent. *Ecol. Appl.* **17,** 1424–1440 (2007).
22. GEO BC. Digital Elevation Model. *Government of British Columbia Data Catalogue* (2011). Available at: http://catalogue.data.gov.bc.ca/dataset/bc-1-250-000-digital-elevation-model.
23. ESRI. ArcMap 10. (2010).
24. Rho, P. Wetness: An Avenue Script for ArcView 3.2. (2002).
25. Evans, J. Topographic ruggedness index. (2004).
26. NASA Land Processes Distributed Active Archive Center Products. LANDSAT 8 Imagery. (2014).
27. Baig, M. H. A., Lifu, Z., Shuai, T. & Tong, Q. Derivation of a tasselled cap transformation based on Landsat 8 at-satellite reflectance. *Remote Sensing Letters* 423–431 (2014).
28. Northrup, J. M. *et al.* Vehicle traffic shapes grizzly bear behaviour on a multiple-use landscape. *J. Appl. Ecol.* **49,** 1159–1167 (2012).
29. Boyce, M. S. & McDonald, L. L. Relating populations to habitats using resource selection functions. *Trends Ecol. Evol.* **14,** 268–272 (1999).
30. Proctor, M. F. *et al.* Population fragmentation and inter-ecosystem movements of grizzly bears in Western Canada and the Northern United States. *Wildl. Monogr.* 1–46 (2012). doi:10.1002/wmon.6
31. Kendall, K. C. *et al.* Demography and Genetic Structure of a Recovering Grizzly Bear Population. *J. Wildl. Manage.* **73,** 3–17 (2009).
32. McLellan, B. N. *et al.* Rates and causes of grizzly bear mortality in the interior mountains of

British Columbia, Alberta, Montana, Washington, and Idaho. *J. Wildl. Manage.* **63,** 911–920 (1999).

33. ESRI. World Imagery ‘Digital Globe’.

34. McRae, B. H. & Kavanagh, D. M. Linkage mapper connectivity analysis software. (2011).

35. McRae, B. H. Pinchpoint mapper connectivity analysis software. (2012).

36. McLellan, M. L. *et al.* Divergent population trends five to sixteen years after ending the legal grizzly bear hunt in southwestern British Columbia, Canada.

37. Nielsen, S. E., Boyce, M. S., Stenhouse, G. & Munro, R. Modeling grizzly bear habitats in the Yellowhead ecosystem of Alberta: taking autocorrelation seriously. *Ursus* **13,** 45–56 (2002).

38. Chetkiewicz, C. L. B. & Boyce, M. S. Use of resource selection functions to identify conservation corridors. *J. Appl. Ecol.* **46,** 1036–1047 (2009).

39. McLellan, M. L. *Ecological relationships between grizzly bears and forest management in the coast-interior transition of southern British Columbia: 2007 field season progress report.* (2007).

Appendix I: GIS Data Layers

Habitat: These are the input layers used for analysis in the linkage mapper and associated tools. These layers are grizzly bear specific and are specific to this study area.

Habitat.gdb	
BuildD_500m	layer identifying building density in the 500m^2 surrounding each
CORE	Clusters of good habitat identified from the RSF over 2.3km^2 (Average daily distance moved for female grizzlies in these populations).
InverseRSF	Inverse RSF used as a resistance layer for bear movement.
RSF_MAP	Application of the exponential equation to each pixel identifying the relative odds of selection.

Linkage geodatabase includes files each describing attributes of connectivity between core habitat areas including connectivity across current population fractures.

Linkage.gdb	
Corridors	Cumulative least-cost corridors.
Corridors_truncated_at_200k	Same as above but truncated but largely irrelevant.
Current_adjacentPairs_50K	Current flow identifying potential pinch points in connectivity.
CWD	Cost-weighted distance path. The least accumulative cost required to move between a cell and a specified source. Good for identifying barrier effects.
Inactive_LCPs	Least-cost paths between core areas.
LCPs	Least-cost paths between core areas.

Habitat only resistance layer. The files in this geodatabase do not consider building density in the resistance to movement between core areas.

No_Buildings.gdb	
NB_corridors	Cumulative least-cost corridors without buildings in resistance layer.
NB_corridors_truncated_at_200k	Same as above but truncated but largely irrelevant.
NB_current_adjacentPairs_50K	Current flow identifying potential pinch points in connectivity.
NB_cwd	Cost-weighted distance path. The least accumulative cost required to move between a cell and a specified source. Good for identifying barrier effects.
NB_Inactive_LCPs	Least-cost paths between core areas.
NB_LCPs	Least-cost paths between core areas.

Appendix II: Supplemental figures

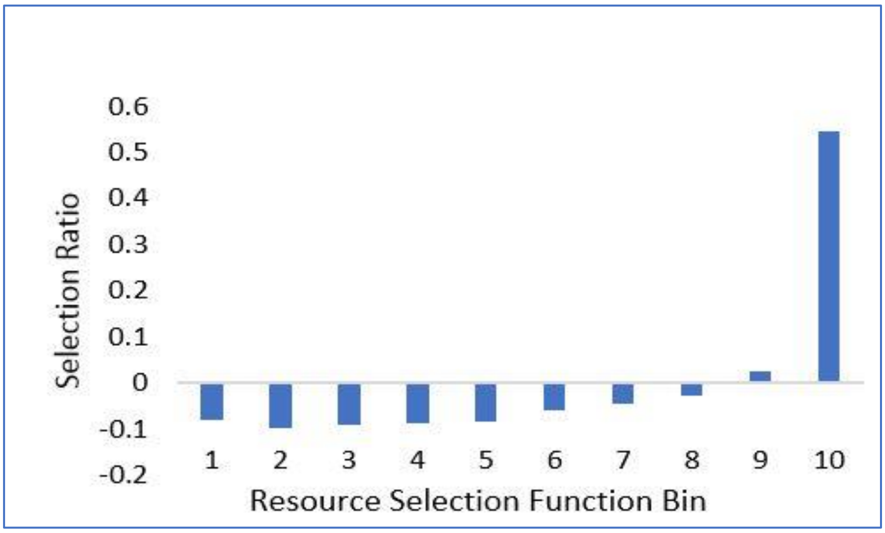

Figure 1: Habitat selection ratio (use/availability) relative to quantile bins depicting equal availability within each bin.

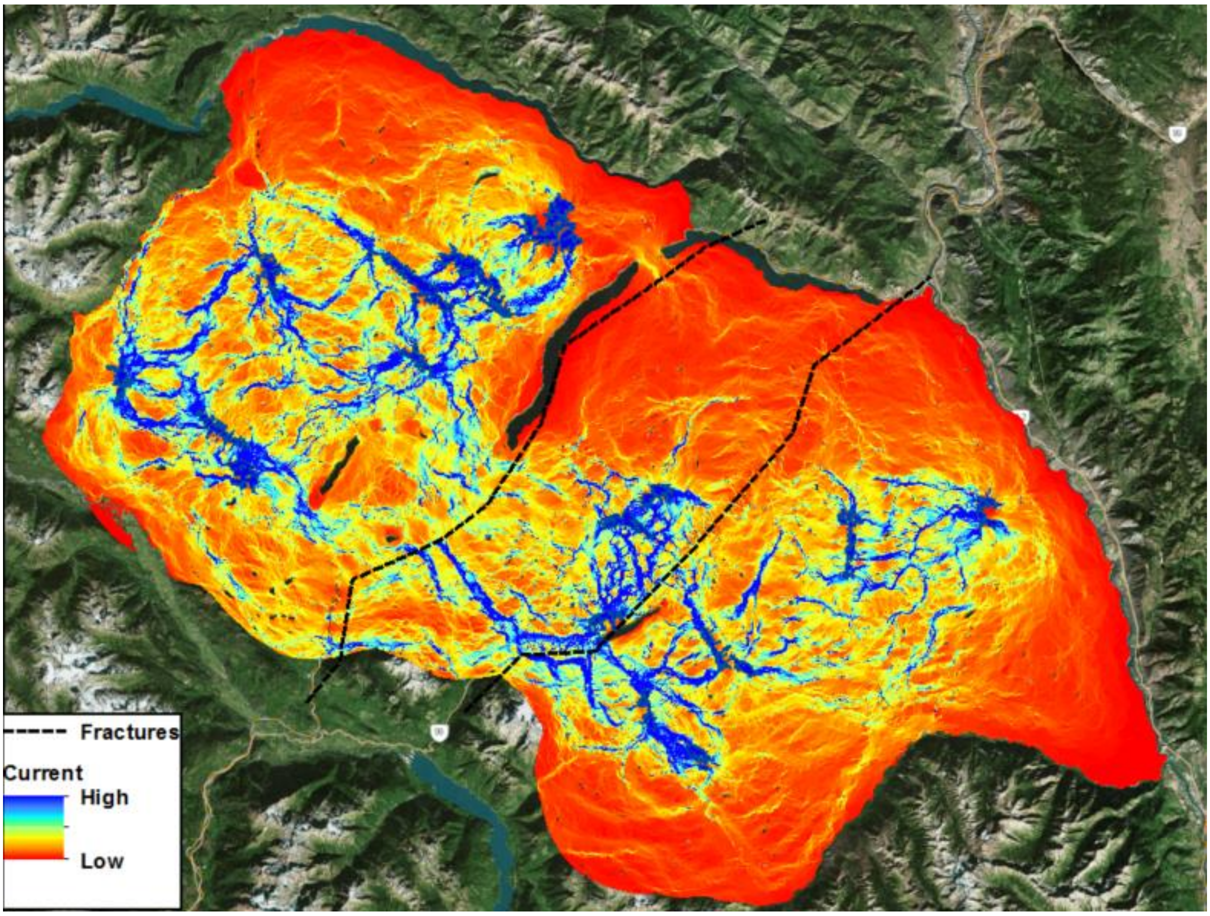

Figure 2: Current flow estimated between core habitat areas identified using circuit theory and pinch-point mapping. Current is proportional to the probability that a dispersing bear will use that path when moving across the landscape. Black lines represent population or demographic factures considered in this analysis.

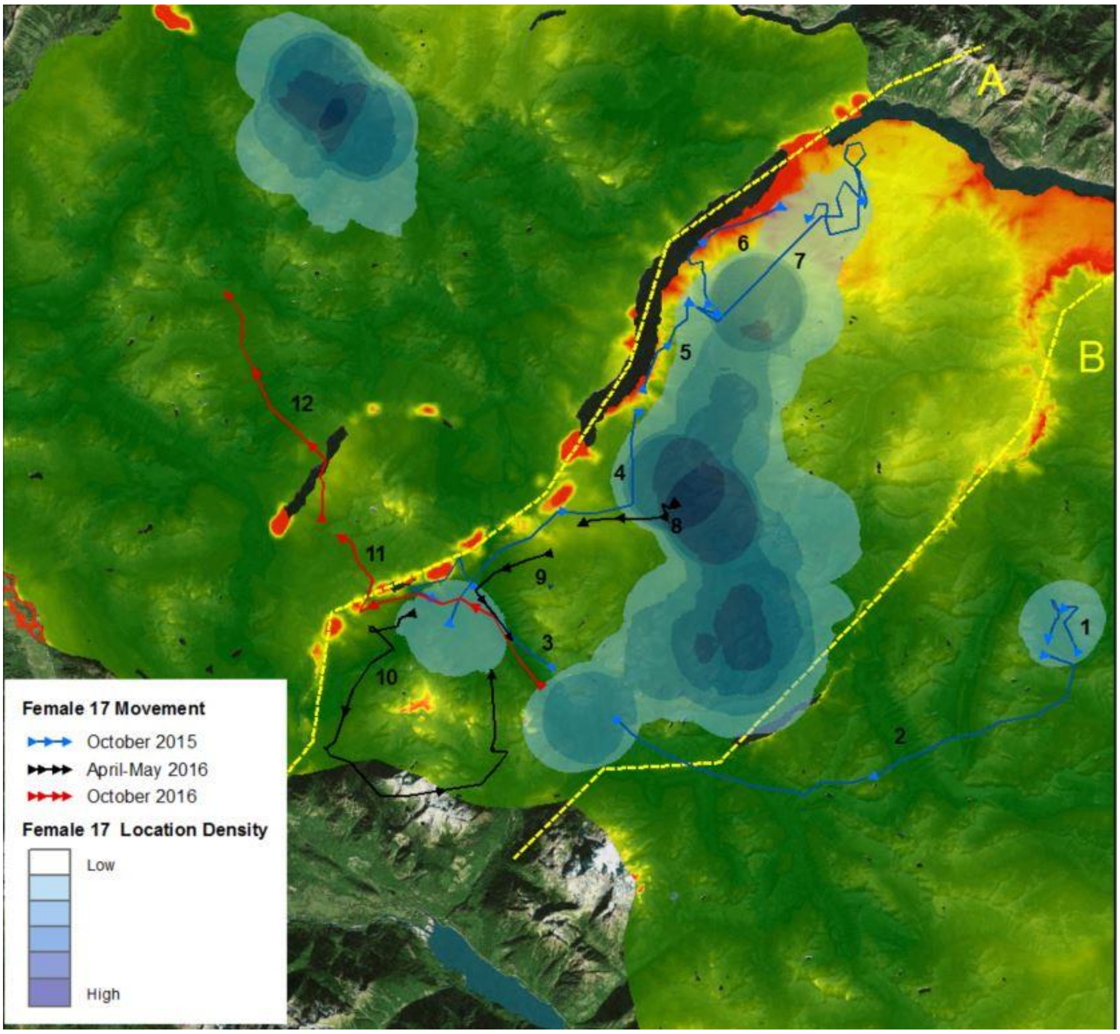

Figure 3: Cumulative least-cost corridor model overlayed by location density of a translocated female showing the areas where she spent the most of her time while collared. Movement pathways and directions depicted by lines 1-12 showing the order in which they took place. Yellow dotted lines show the approximate fractures A and B.