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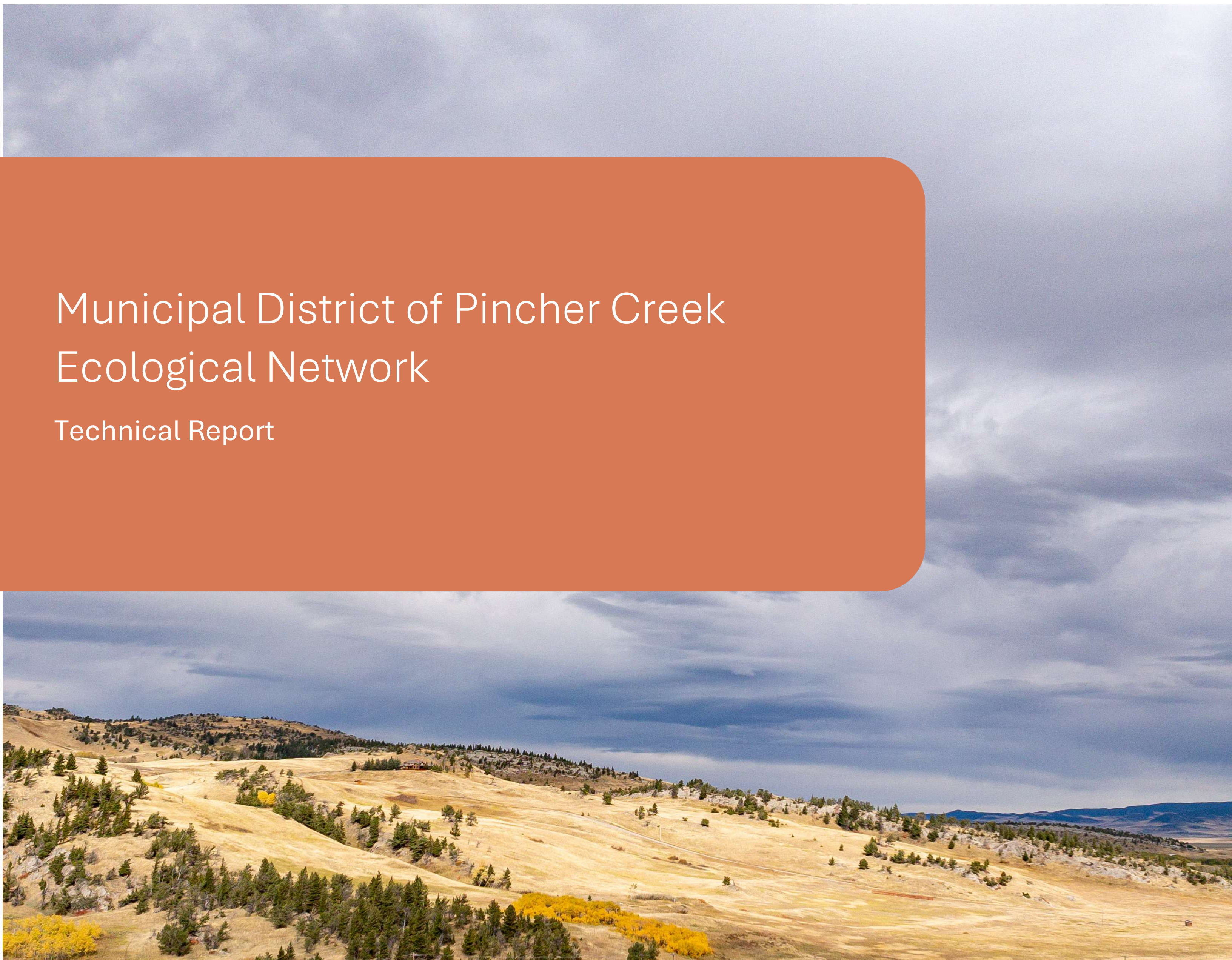

Municipal District of Pincher Creek Ecological Network

Technical Report

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DOCUMENT PREPARED FOR THE MUNICIPAL DISTRICT OF PINCHER CREEK

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Contents

Acknowledgements 4
Executive Summary 5
Introduction 6
Study Area 6
Methods 7
Methodology Overview 7
Structural Connectivity 8
Species-Specific Validation 8
Elk 8
Bears 8
Other Species 9
Connectivity Categories 9
Animal Vehicle Collision Clusters and Alignment with Connectivity 9
Practitioners workshop 10
Results 11
Structural Connectivity 11
Species-Specific Models and Validation 12
Elk 12
Bears 15
Moose 16
Badger 18
Connectivity Categories 19
Risk of Land Use Change 22
Ecological Network Delineation 23
Animal Vehicle Collision and Connectivity 24
Practitioners Workshop 28
Discussion 30
Structural connectivity as representative of terrestrial animal movement 30
Classification of structural connectivity into connectivity categories, land management type, and road sections. 31
References 33
Appendix A: Animal Vehicle Collision (AVC) plots 36

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Executive Summary

This report presents an ecological network for the Municipal District of Pincher Creek, developed using a structural connectivity modeling framework. Structural connectivity is species-agnostic and describes how well areas of natural or semi-natural land are physically connected across the landscape. It reflects the arrangement and continuity of natural features, such as vegetation, topography, and land cover, without considering the movement behaviour of particular species. We used the structural connectivity model to represent the movement needs of terrestrial mammals and validated the model using species-specific movement and occurrence data. We tested if our structural connectivity model spatially represented movement of several terrestrial mammal species by comparing the model against an elk GPS collar dataset, and moose, grizzly bear, black bear, and badger occurrence records. Our results highlight the value and complexity in trying to delineate an ecological network using structural connectivity. Elk and moose were well represented in areas with higher structural connectivity value including five different movement types for elk. For ungulates areas of medium to high structural connectivity values represented movement needs well. Species that exhibit movement influenced by behavioral responses to human altered landscape features such as grizzly bears, black bear or badger were not as well represented by the structural connectivity model. We recommend future phases of research consider species-specific functional connectivity models, which include animal behavior to improve landscape management strategies for the movement of large terrestrial species.

A major challenge in developing effective conservation strategies is the abstract nature of connectivity models, which are often displayed simply as gradients from low to high values. To make these models more practical for planning, the structural connectivity results for the Municipal District of Pincher Creek were grouped into three categories: channelized (movement is concentrated into narrow channel), diffuse (movement is distributed over a larger area), and impeded (movement is more restricted). These categories help illustrate where terrestrial mammal movement is constrained or more flexible. Channelized areas indicate key movement corridors that may require protection or policy integration, while diffuse areas represent broader, more permeable landscapes where stewardship and coexistence initiatives, such as wildlife-friendly fencing, can maintain movement opportunities.

When these connectivity categories were mapped by landownership type, 51% of the important connectivity areas were found on provincially managed lands. This underscores the need for coordination across multiple provincial ministries with varying mandates, such as transportation, forestry, tourism, and energy. The remaining 49% of connectivity areas occur on private lands, including 12% under conservation ownership or easement. This distribution points to both opportunities and gaps—while roughly half of the connected areas already benefit from some form of protection, voluntary conservation incentives on private agricultural lands could further enhance habitat connectivity.

Zoning analysis showed that 40% of channelized and diffuse areas are within Provincial Parks and are 60% within agricultural zones, suggesting that current land-use designations are generally compatible with maintaining connectivity. Conservation practitioners emphasized the importance of reviewing municipal plans, such as Area Structure Plans, to ensure that future development does not compromise movement corridors. Additionally, overlap between high-flow connectivity areas and wildlife–vehicle collision clusters highlight opportunities for road mitigation measures like crossing structures and fencing. Collectively, these findings inform a suite of conservation strategies for the Municipal District of Pincher Creek's forthcoming connectivity action plan, including policy integration, private-land conservation incentives, infrastructure mitigation, coordinated public-land management, and Indigenous-led stewardship.

Introduction

A naturally connected system, or ecological connectivity, enables provisioning of ecosystem services, as well as the opportunity for plants and animals to shift ranges in response to climate change or other disturbances (Carroll et al., 2018; Chen et al., 2011; Taylor et al., 1993). In southwestern Alberta, the Municipal District (MD) of Pincher Creek contains a diverse mosaic of grasslands, foothills, and forested slopes, forming a key part of the Crown of the Continent Ecosystem. This landscape supports a range of large and wide-ranging mammals including deer, wolves, wolverine, elk, moose, grizzly bear, and bighorn sheep, as well as a high diversity of native flora and fauna.

Maintaining ecological connectivity is critical to the long-term resilience of wildlife populations and ecosystems (Belote et al., 2022; Pither et al., 2023). However, as land use in and around Pincher Creek continues to evolve, driven by agriculture, rural development, recreation and tourism, renewable energy, and infrastructure expansion, the ability of wildlife to move across the landscape could be compromised without careful consideration of how and where growth occurs. Identifying, understanding, and maintaining ecological connectivity within this region is increasingly important for effective land-use planning, biodiversity conservation, and preservation of the landscape (Beger et al., 2022; Haber & Nelson, 2015; Huber et al., 2012; Keeley et al., 2019).

This report presents a map of an ecological network for the Municipal District of Pincher Creek (MDPC), representing where terrestrial wide-ranging mammals are most likely to travel within the MDPC, either within their home ranges or between important areas required for their continued persistence. The map was developed using a structural connectivity (represents a measure of naturalness (e.g. forests, grasslands) and how connected the natural landscape is) modeling framework (Marrec et al., 2020). We test whether the structural model is representative of terrestrial mammal movement needs using species-specific movement and occurrence data (Pither et al., 2023). We then classify the connectivity model into connectivity classes focused on pinch points, flexibility, and impediments to mammal movement to inform land use planning and management actions (Cameron et al., 2022). This forms the basis for developing strategies specific to connectivity class that will maintain or improve terrestrial mammal movement. The ecological network was further refined through engagement with Municipal District planning staff and local conservation practitioners with expertise in ecological connectivity.

The resulting ecological network is intended to inform local planning decisions that support both ecological and community values by highlighting areas of important ecological connectivity, identifying core habitat blocks, and mapping road segments with elevated risks of animal-vehicle collisions. The report also considers the varying jurisdictions and zoning in Pincher Creek as a foundation for integrating connectivity strategies in an area of diverse land management. This work provides decision-makers, landowners, and communities with spatial tools and insights to help guide sustainable land-use decisions in the MDPC.

Study Area

The Municipal District of Pincher Creek (MDPC) is in southwestern Alberta, Canada, and encompasses a diverse landscape of prairie grasslands, foothills, and the eastern slopes of the Rocky Mountains. Covering an area of approximately 3,500 square kilometers, it is known for its stunning natural scenery that supports rich biodiversity. The region features a mix of agricultural lands, renewable energy, natural resource extraction, rural residential communities, and protected areas, making it a unique interface of human activity and natural ecosystems. The district's varied topography and habitat types provide critical connectivity for wildlife. Its climate is characterized by Chinook winds and variable precipitation which contribute to its ecological complexity.

The area's land ownership consists of 60% private landownership and 39% crown ownership, including parks, public lands management by different Government of Alberta (GOA) ministries, and less than one percent municipal lands. The district is part of Treaty 7 which includes Blackfoot Nations including Siksika First Nation, Piikani First Nation, and Kiana First Nation, Tsuut'ina Nation, and Stoney Dakota Nations including Bearspaw First Nation, Chiniki First Nation, and Goodstoney First Nation.

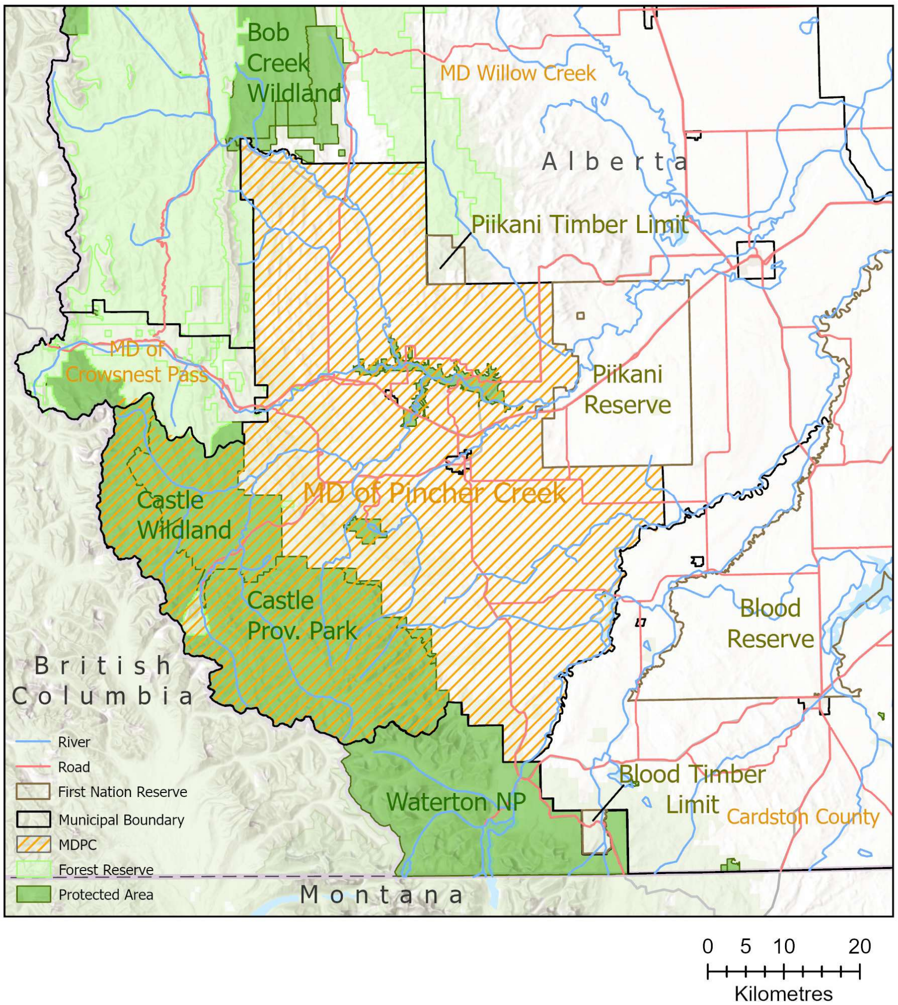

Figure 1: Municipal District of Pincher Creek (MDPC) in Alberta, Canada.

Methods

Methodology Overview

The structural connectivity model is based on a resistance surface (pixelated map in which each pixel is assigned a numerical value that represents the estimated difficulty of moving through a specific area) of 30 × 30 m resolution, incorporating human modifications, large water bodies, and steep slopes. The resulting connectivity model was validated using species-specific data from elk, bears, moose, and badgers using a Poisson generalized linear model (glm). Additional spatial datasets were developed to inform the development of a connectivity plan for the Municipal District of Pincher Creek (MDPC):

- Connectivity was categorized into channelized (movement is concentrated into a narrow channel), diffuse (movement is distributed over a larger area), and impeded (movement is more restricted), based on structural connectivity bins;
- Connectivity categories of channelized and diffuse were displayed per land management type and municipal zoning to show areas of connectivity; and
- Alignment of where animal-vehicle collisions (AVCs) clusters intersect with areas of higher connectivity value.

Spatial datasets were presented to collaborators for feedback and to outline conservation strategies to improve connectivity.

Structural Connectivity

We developed a structural connectivity model following the conceptual framework developed by Marrec et al. (2020). We generated a resistance surface of 30 × 30 m resolution based on human modification of the landscape, large water bodies, and slopes greater than 30 degrees. We used the same human modification values from 0 (no human modified features) to 1 (high level of human modification and barrier to natural systems) generated by an expert committee in Alberta (Marrec et al., 2020), and added scores for larger water bodies (named lakes [0.75] and major rivers [0.50] and slopes greater than 30 degrees [0.75]). We generated water and slope values based on our overall purpose to support movement areas of terrestrial mammals. We used fuzzy algebra to combine overlapping human footprint layers (e.g., roads, development, and land use) so that each pixel was assigned a single resistance value. This approach accounts for the combined influence of multiple disturbance types by weighting areas where pressures overlap more heavily than where only one occurs. We used nodes generated around the edge of the study area and ran a Circuitscape model in JULIAN (Anantharaman et al., 2020). We then reclassified the structural connectivity model into five bins based on quantiles of low to high flow.

Species-Specific Validation

Elk

We acquired elk collar data from the Rocky Mountain Montane Elk Project for 182 individuals captured between 2007 - 2011 and it identified six movement types: summer, winter, spring, fall, dispersal (a one-time long-distance movement to new range), and resident (individuals that remain in a small, familiar area throughout the year). We classified elk movement types using Migration Mapper software (Merkle et al., 2022). We mapped each movement type using population use contours, which display areas of equal population density on a map, to highlight areas with increased use based on where multiple animals had spent the most time. During classification of movement types in Migration Mapper we noted dispersal behavior, defined as a long unique movement whereby the animal did not return to starting point within the available dataset.

We assessed the ability of the structural connectivity model to represent different movement types for individual elk by comparing the elk collar data per six movement types to structural connectivity model classified into five bins (quantiles). We then applied Poisson generalized linear model (glm), used to analyze count data where the logarithm of the expected count is modeled as a linear combination of the predictor variables, for each movement type and accounted for individual elk behaviors.

Bears

We obtained grizzly and black bear data from University of Alberta based on a study of 871 rub objects that were surveyed for hair samples and from the GOA Fish Wildlife Information Management System (FWMIS). For the rub tree dataset we used the positive identification results for both grizzly bear and black bear to compare with the reclassified structural connectivity. We then applied Poisson generalized linear model (glm) to determine if there is a relationship between structural connectivity model and bear detections for each species.

Other Species

We obtained badger and moose data from GOA's FWMIS. We used 568 moose detection reported between 2014 to 2022 and 64 badger observations from 1996 to 2022. We used the species specific FWMIS data to compare to the reclassified structural connectivity model. We then applied Poisson generalized linear model (glm) for each species to determine if there is a relationship between structural connectivity model and moose or badger.

Connectivity Categories

To support the development of targeted strategies for maintaining connectivity, we modified a spatially explicit framework developed by Cameron et al (2022). Because movement opportunities and challenges will vary across the landscape and land management contexts, we sought to categorize types of connectivity based on urgency for maintaining connectivity. For instance, areas where wildlife movement are restricted into pinch point would be considered more urgent to maintain, as their loss could sever connectivity entirely. We developed connectivity categories using results from the mammal species validation to identify:

1. Channelized areas (bin 5) represent areas where flow based on naturalness is more concentrated and could represent pinch points for wildlife movement.
2. Diffuse areas (bin 3 and 4) represent areas where flow based on naturalness is less concentrated and there may be more options for wildlife movement.
3. Impediment areas (bin 1-2) represent areas where flow based on naturalness is more limited and wildlife may have more difficulty moving through the area.

To further aid in the development of strategies to maintain ecological connectivity, we identified the land management type for the channelized and diffuse areas. We overlaid municipal zoning to identify the opportunity areas (where zoning supports wildlife movement) and conflict areas (where zoning is problematic for wildlife movement). Lastly, we identified landownership categories as lower or higher risk of development (E.g., residential, industrial, ect.) and displayed this on channelized and diffuse areas.

Animal Vehicle Collision Clusters and Alignment with Connectivity

We aimed to identify where structural connectivity aligns with AVC clusters on the provincial highway network to inform restoration strategies associated with roads and wildlife. To determine where AVCs occur we used Alberta Wildlife Watch (AWW) carcass data provided by the GOA from 2018 to 2023. We applied KDE+ open-source software that analyzes observation clusters with repeated random simulations (Monte Carlo method) to objectively determine their significance (thresholds) based on cluster strength (Bíl et al., 2016). Alberta Transportation and Economic Corridors (TEC) used a similar method to identify clusters of provincial significance and guide investment in road mitigation to reduce risks to motorist safety (Alberta Transportation and Economic Corridors, 2023b).

To run the KDE+ analysis, we adjusted AWW carcass locations to align with the nearest provincial highway (using a 100 m buffer) and ran KDE+ in ArcMap using a 100 m moving window. To display results, we used KDE+ cluster strength definitions; the strongest and most stable clusters are those with a strength ≥ 0.55 and at least 5 carcass records per cluster (Bíl et al., 2016). Weaker clusters are those with strength < 0.55 and/or 4 or fewer carcass records per cluster. Cluster strength is important as these rankings are used to identify areas where road mitigation investment is justified to reduce AVCs through the AWW program. AVC clusters represent areas with greatest motorist safety risk and only include medium to larger mammals in the analysis as these represent greatest risk to motorist safety. The clusters to not distinguish between size of large mammal species, treating all carcasses same in analysis.

We also attributed the cost of AVCs for ungulate species (deer, elk, moose and bighorn sheep) and large carnivores (bear, cougar) using cost values (vehicle repair, human injuries, human fatalities) recommended by Huijser et al. (2022) (Table 1). The average AVC cost per km was calculated by assigning AWW species counts to a km road section, multiplying ungulate species and grizzly bear by their specified costs per km, summing the costs per km and averaging total cost by the five-year period. The costs of collisions were first calculated in United States dollars (USD), and the totals were converted to Canadian dollars (CDN). In addition, research indicates for every animal carcass reported via carcass reporting systems, 2.8 additional carcasses can be found within 150 m of the road right of way due to injury and death away from the highway right of way (Lee et al., 2021). We therefore multiplied total AVCs per year and costs of collisions per year with a correction factor of 2.8.

Table 1: Costs per ungulate collision in USD (Huijser et al., 2022). Deer included both mule and white-tailed deer. Grizzly bear, black bears and cougar and bighorn sheep were valued at the same costs as deer spp.

Cost Category	Deer & Grizzly bear	Elk	Moose
Vehicle repair	$4,418	$7,666	$9,535
Human injuries	$6,116	$14,579	$26,811
Human fatalities	$3,480	$23,200	$46,400
Total	$14,014	$45,445	$82,646

The AWW Program uses a different approach to model costs whereby $100,000 CDN is applied AWW large mammal collision records (Alberta Transportation and Economic Corridors, 2023b). We calculated AWW Program cost per km based on the same set of species listed above to compare costs per annum.

To identify road sections of alignment between AVC clusters and structural connectivity we assigned values to one kilometer section and created indexes. Road kilometer sections were provided by Transportation and Economic Corridors. To determine the connectivity value per road section we log transformed the structural connectivity values and then applied a 200 m buffer to each road section and calculated the mean connectivity value within the buffer zone to represent the connectivity value per road section. We then normalized the data to create the index. To generate the AVC cluster values per road section, we used the strength field from the KDE+ result and assigned this value to each road section. If a cluster spanned two road sections, we assigned the KDE+ strength value to both road sections. If a road section was represented by more than one cluster, we assigned the max value. We then normalized the data to create an AVC index. Indexes ranged from 0 to 1, whereby 0 is no AVC/low connectivity value and 1 is high AVC/high connectivity value.

We plotted the AVC and connectivity indexes in a quadrant plot based on a threshold of 0.5 and displayed results per road section for high AVC/high connectivity value, high AVC/low connectivity value, low AVC/ high connectivity value and low AVC/low connectivity value.

Practitioners workshop

Maps of the spatial datasets were presented at a workshop with 17 conservation practitioners from provincial and municipal government agencies, an Indigenous Nation, land trusts and conservation organizations working in the area. Workshop participants had local expertise in land management, land use policy and planning, and wildlife movement. The maps were shared via a MIRO board to allow participants to interact with the mapping products and comment or identify areas of concern directly on the map. Workshop participants were asked the following questions while reviewing spatial products: are there geographical areas not included in the structural connectivity modelling and habitat patches;

does the categorization of channelized and diffuse help with strategy development; which GOA Ministries should be part of strategy development; how can we best prioritize key parcels of land; what the barriers to maintaining crown lands; what are the gaps in legal and policy tools; and what are key conservation strategies for maintaining an ecological network for terrestrial large mammals. We tabulated the input from the workshop and summarized the strategies specific to each land manager. The results were used to inform the final spatial datasets and a corridor conservation action plan.

Results

Structural Connectivity

A structural connectivity model is displayed in Figure 2 based on five quantiles whereby a value of 5 represents area with highest flow and value of 1 is lowest or minimal flow. Flow represents the movement of animals across the landscape under varying resistances.

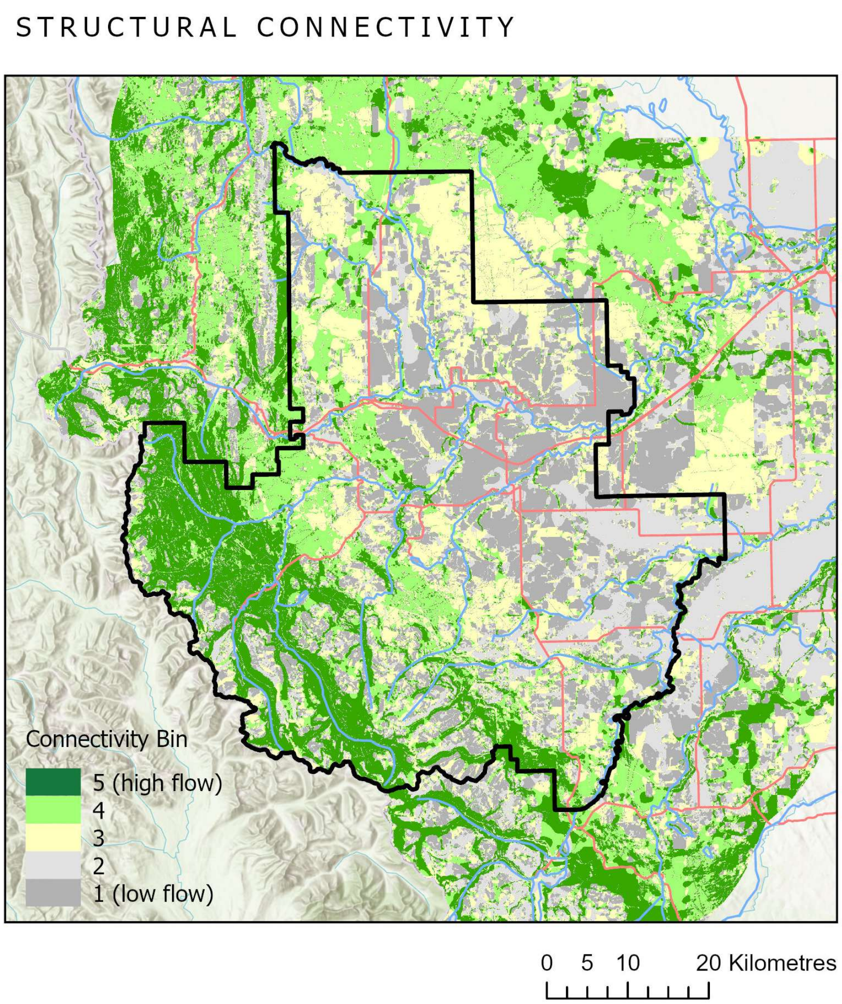

Figure 2: Structural Connectivity model displayed in five quantiles (from high flow (dark green/ bin 5) to low flow (yellow/bin 1) of connectivity for the MDPC, Alberta.

Species-Specific Models and Validation

To determine how well the structural connectivity model represents movement of terrestrial mammal species we compared existing movement or occurrences data for elk, grizzly bear, black bear, moose, and badger.

Elk

Elk use of the landscape changes depending on the season and weather conditions, with distinct habitat areas in the summer and winter (Figure 3). Migratory movements between the summer and winter range included stopovers and some non-stereotypical movements back and forth between the summer and winter habitat during the migratory period (Figure 4). Dispersing individuals moved long distances over short periods of time during the spring to occupy a different area of the landscape and did not return the following year (Figure 4). Lastly 30 individuals remained in one area with no migratory movements and were classified as resident elk (Figure 5).

ELK SUMMER AND WINTER RANGE

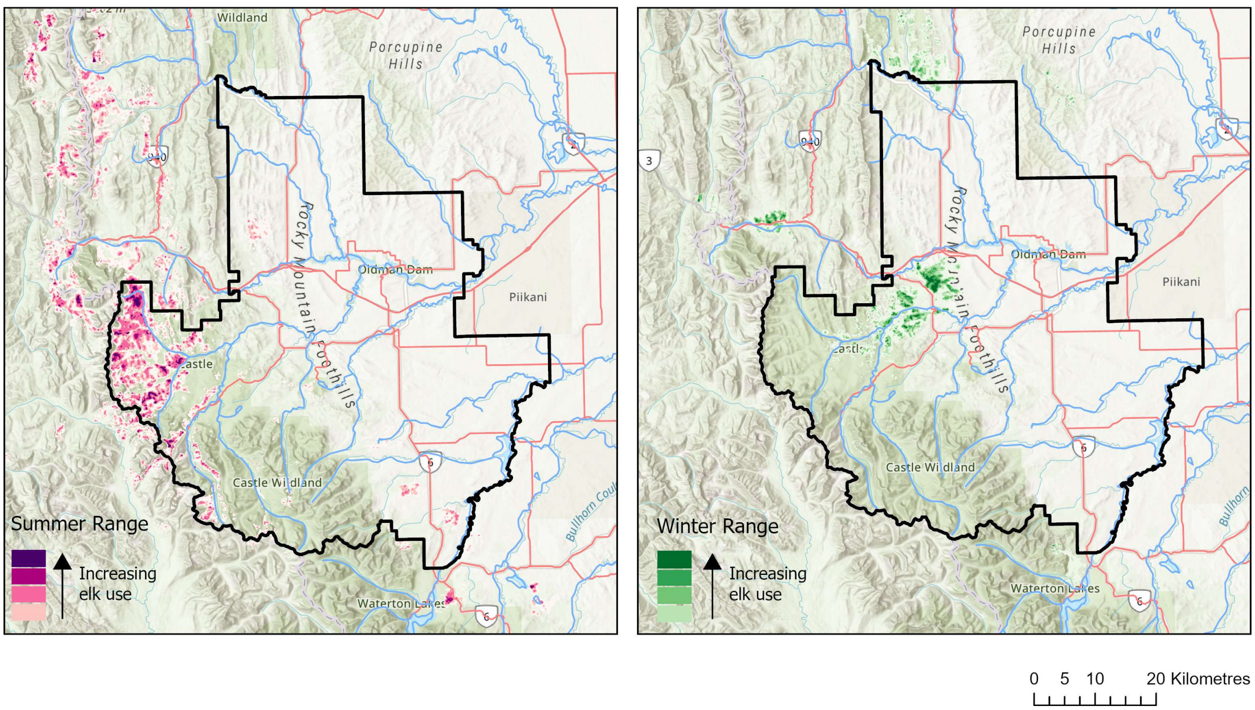

Figure 3: Elk population use area for summer habitat (increasing with use from light pink to dark pink) and winter habitat (increasing with use from light green to dark green) for MDPC, Alberta.

ELK MIGRATION AND DISPERSAL

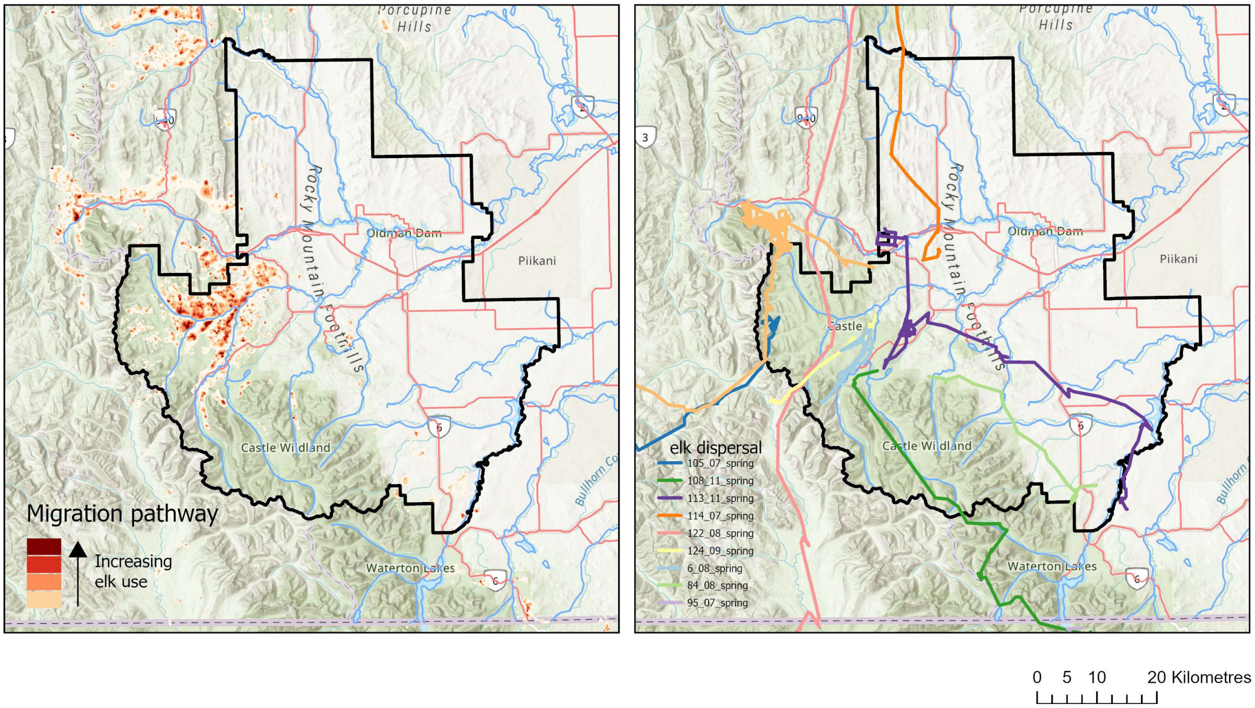

Figure 4: Elk population use area for spring and fall migration (increasing use from light orange to dark orange) and dispersing elk movements for the MDPC, Alberta.

ELK RESIDENT ANIMALS

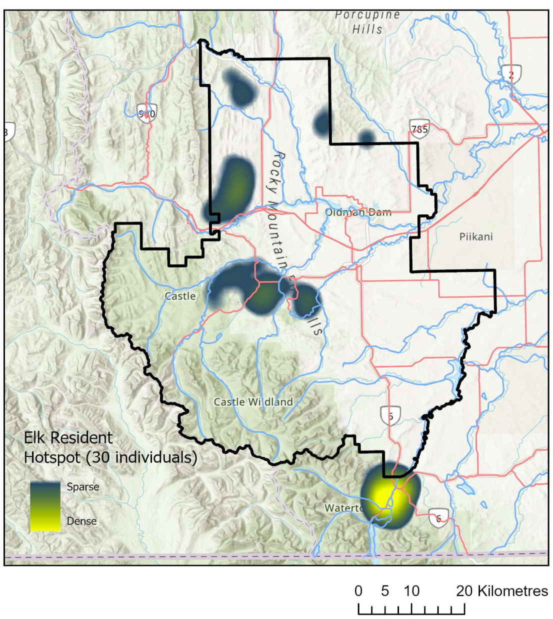

Figure 5: Elk population use area for resident animals (increasing use from blue to yellow) and for the MDPC, Alberta.

The generalized linear mixed model (GLMM) for elk movement indicate structural connectivity (as represented by the connectivity bins) is a strong predictor of movement frequency, but the magnitude of the effect and the baseline movement frequency vary by movement type (Table 2, Figure 6). Elk had higher use in connectivity bins 3, 4, and 5 for all movement types with the strongest association in summer and winter. Individual elk variability is also present, though it is lower for some movement types (Winter, Resident) than for others (Summer, Fall, Spring, Dispersal) (Figure 7).

Table 2: Generalized linear mixed model with a Poisson distribution for elk movement types per connectivity bin indicates multiplicity (multiple comparisons between bins) over reference bin (bin1) and random effects variance per individual elk. Exponential is abbreviated to Exp in the table headings and standard deviation is abbreviated to SD.

Movement	Obs.	Intercept	Bin2	Bin2 Exp	Bin3	Bin3 Exp	Bin4	Bin4 Exp	Bin5	Bin5 Exp	Random Var	Random SD
Summer	773	3.43	-0.34	0.71	0.57	1.78	1.19	3.29	2.69	14.80	1.22	1.10
Winter	344	4.57	-0.72	0.49	1.15	3.14	2.17	8.75	1.16	3.18	0.18	0.43
Fall	597	1.62	-0.27	0.76	0.80	2.22	1.91	6.75	2.44	11.44	1.02	1.01
Spring	755	1.56	-0.34	0.71	0.85	2.34	1.75	5.75	2.16	8.66	1.02	1.01
Dispersal	79	1.69	-0.08	0.92	1.07	2.92	1.60	4.97	2.33	10.29	0.96	0.98
Resident	344	4.57	-0.72	0.49	1.15	3.14	2.17	8.75	1.16	3.18	0.18	0.43

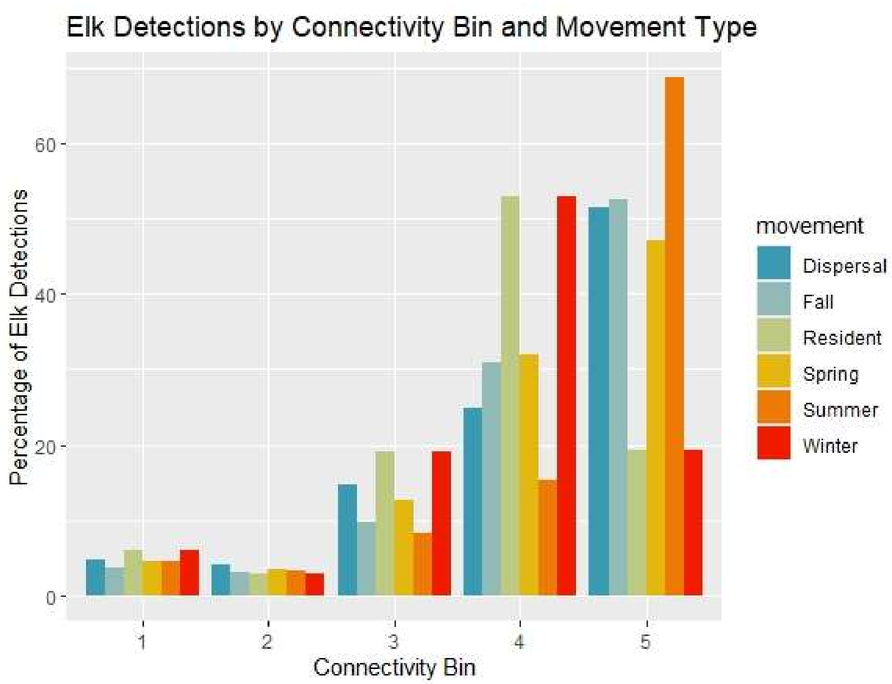

Figure 6: Percent of elk detections across connectivity bins for six movement types (Summer, Winter, Fall, Spring, Dispersal, and Resident). Connectivity bins 1-2 represent impediment areas, bins 3-4 represent diffuse areas, and bin 5 represents channelized areas.

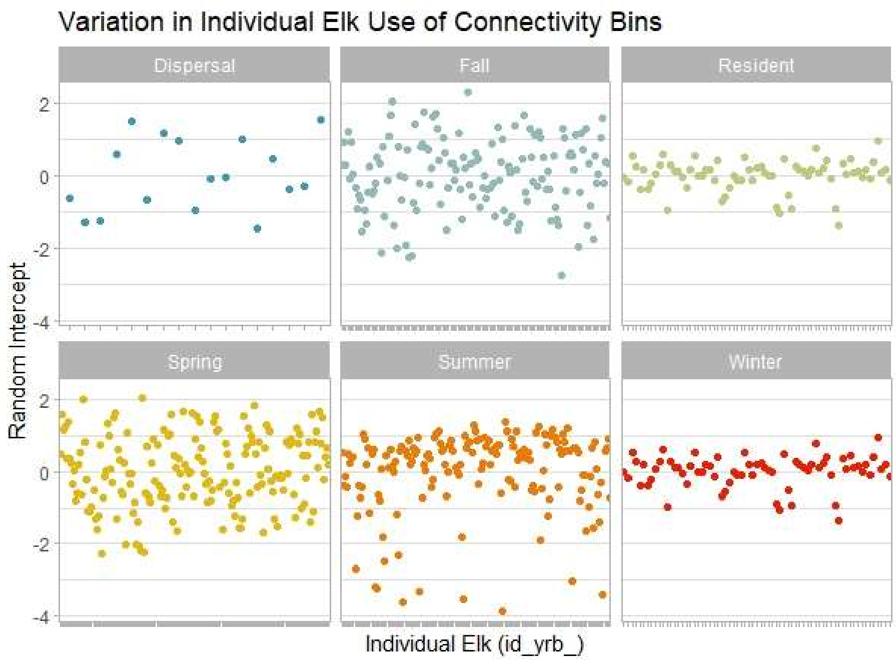

Figure 7: Individual variation in elk movement across six movement types. Points closer to 0 indicate less variation among individuals in the connectivity bins they used. Winter (red) and resident (light green) movement types show the least individual variation.

Bears

We combined bear occurrence records from a University of Alberta bear DNA project (2012-2014) and GOA FWMIS database (2011-2024), resulting in 917 grizzly bears and 1233 black bear detections (Figure 8).

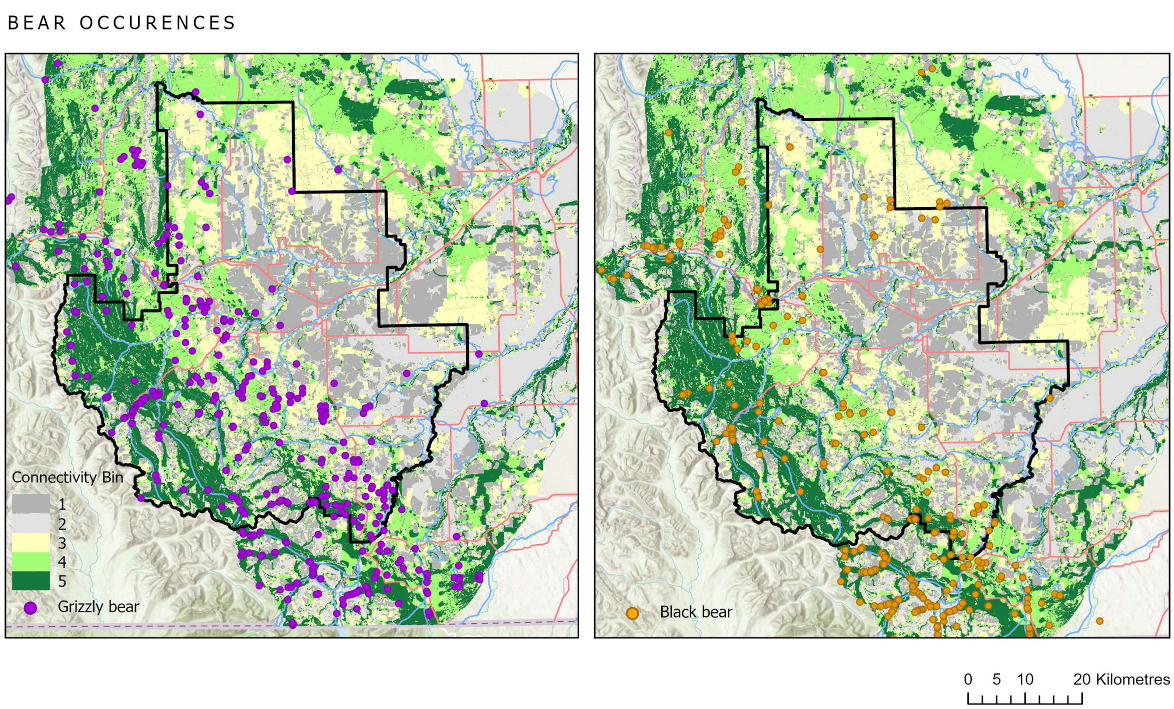

Figure 8: Structural Connectivity in quantile bins where bin 5 connotates high connectivity value (dark green) and bin 1 connotates low connectivity value (dark grey). Grizzly bear occurrences are displayed as purple circles and black bear occurrences are depicted as orange circles for the MDPC, Alberta.

The glm for grizzly bear movement indicates structural connectivity (as represented by the connectivity bins) is a not a strong predictor of movement frequency. Table 3 indicates that grizzly bear counts are highest in bins 1 and 5, indicating a preference for disturbed lands (bin 1) where agricultural associated attractants are common (deadstock compost piles, grain bins, and watering sources for cattle) and lands with highest connectivity value (bin 5). The glm for black bear movement indicates structural connectivity is a good predictor of black bear movement with higher counts in bins 2, 4, and 5 (Figure 9).

Table 3: Results from Poisson model for grizzly and black bear coefficient (estimate log scale) and Incidence Rate Ratio (how many times higher the expected count is compared to the reference bin) where the reference bin is 1.

Species	Term	Estimate	Incidence Rate Ratio	Standard Error	Statistic	P-value
Grizzly Bear	(Intercept)	**5.176**	177.000	**0.075**	68.864	**0.0**
	factor(bin)2	**-0.397**	0.672	**0.119**	-3.349	**0.0008**
	factor(bin)3	**-0.476**	0.621	**0.121**	-3.918	**0.0001**
	factor(bin)4	**-0.340**	0.712	**0.117**	-2.916	**0.0035**
	factor(bin)5	**0.724**	2.062	**0.092**	7.902	**2.75E-15**
Black Bear	(Intercept)	**4.443**	85.000	**0.108**	40.959	**0.00**
	factor(bin)2	**1.699**	5.471	**0.118**	14.406	**4.74E-47**
	factor(bin)3	**-0.365**	0.694	**0.169**	-2.155	**0.0312**
	factor(bin)4	**1.055**	2.871	**0.126**	8.373	**5.64E-17**
	factor(bin)5	**1.495**	4.459	**0.120**	12.456	**1.30E-35**

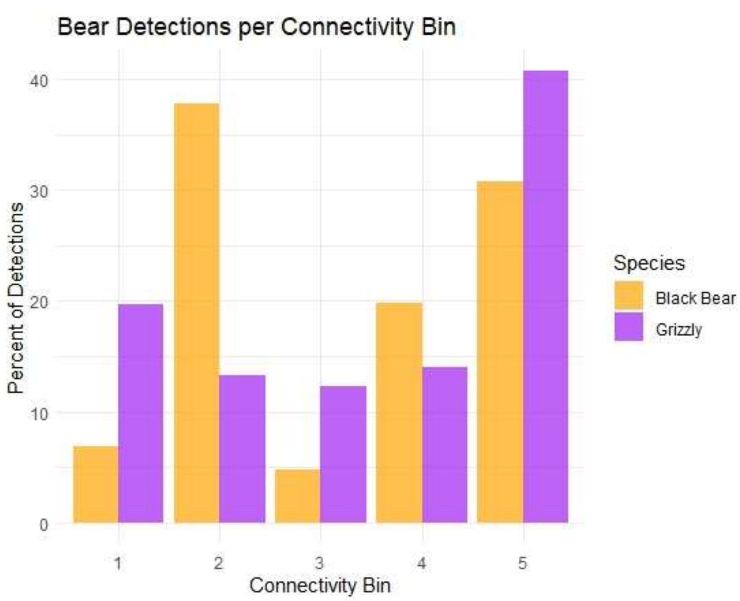

Figure 9: Percent of grizzly and black bear detections per structural connectivity bins where bin 1 has less movement potential and bin 5 has the highest movement potential.

Moose

We extracted moose occurrences from FWMIS data from 2012 for a total of 586 detections in study area (Figure 10).

MOOSE OCCURENCES

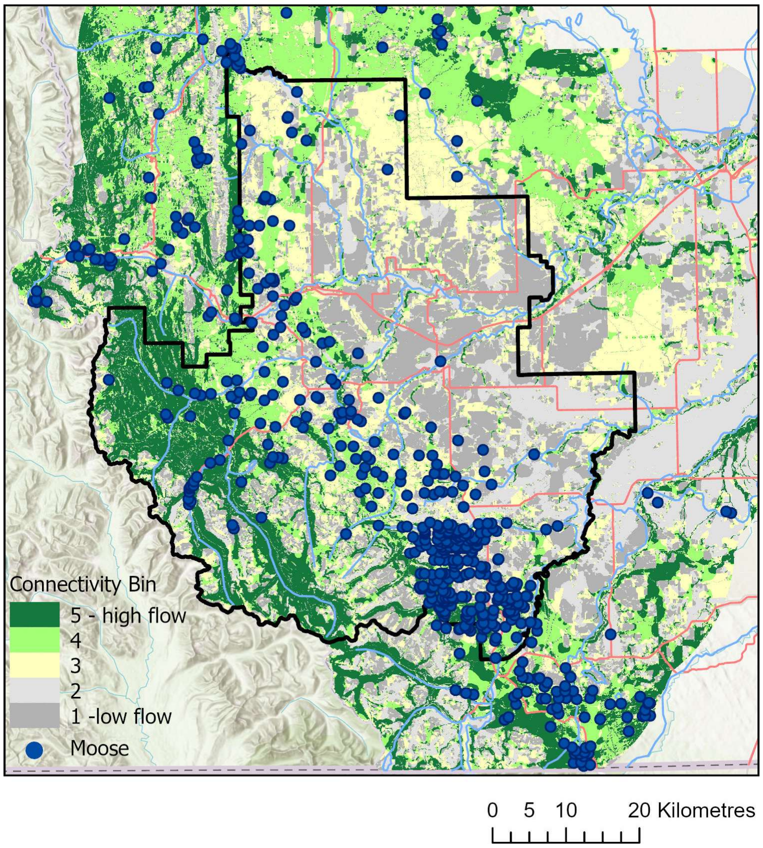

Figure 10: Structural connectivity in five bins from high connectivity value (dark green) to low connectivity value (dark grey) for moose detections in blue where darker clusters represent increasing overlap in location for the Municipal District of Pincher Creek, Alberta.

The glm for moose movement indicate structural connectivity (as represented by the connectivity bins) is a strong predictor of movement frequency. Table 4 indicates moose counts are significantly higher in connectivity bins 2,3,4, and 5 compared to bin 1 (Figure 11).

Table 4: Results from moose Poisson model for moose coefficient (estimate log scale) and Incidence Rate Ratio (how many times higher the expected count is compared to the reference bin) where the reference bin is 1.

Term	Estimate	Incidence Rate Ratio	Standard Error	Statistic	P-value
(Intercept)	3.56	35.00	0.17	21.03	3.220E-98
bin2	0.57	1.77	0.21	2.70	6.842E-03
bin3	1.63	5.09	0.18	8.80	1.416E-18
bin4	1.34	3.80	0.19	7.03	2.106E-12
bin5	1.52	4.57	0.19	8.14	3.805E-16

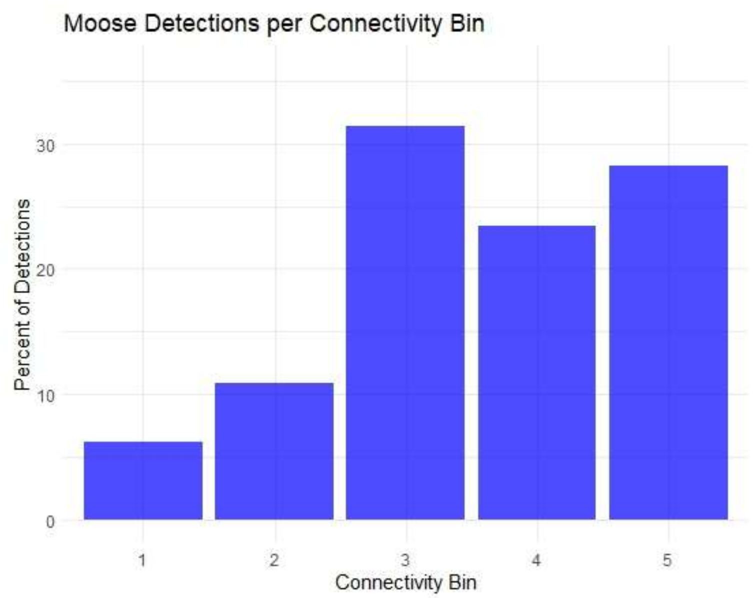

Figure 11: Percent of moose detections per structural connectivity bins where bin 1 has less movement potential and bin 5 has the highest movement potential.

Badger

There are 64 badger occurrences in FWMIS dataset from 1996 to 2022 (all records were kept given the low number of detections).

BADGER OCCURENCES

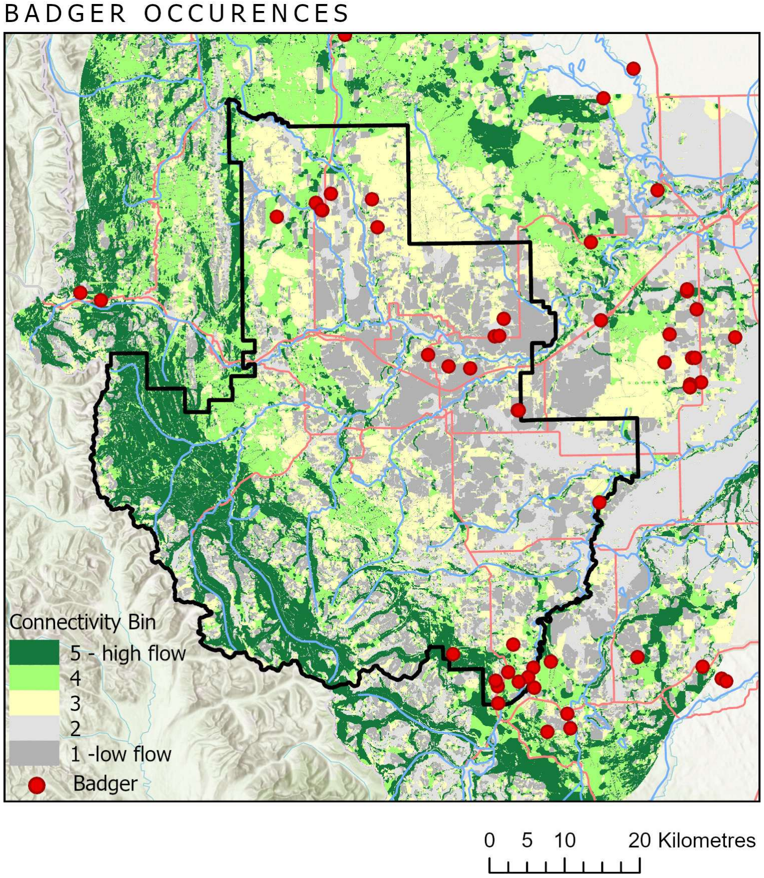

Figure 12: Structural connectivity in five bins from high connectivity value (dark green) to low connectivity value (dark grey) for badger detections (red) in location for the MDPC, Alberta.

Structural connectivity does not represent badger detections well. There is no clear pattern or difference between most bins, possibly due to small sample size (Table 5, Figure 13). Bin 3 has a potential increase in badger counts but is only marginally significant (based on $p < 0.05$, two-tailed).

Table 5: Results from badger Poisson model for moose coefficient (estimate log scale) and IRR (how many times higher the expected count is compared to the reference bin) where the reference bin is 1.

Term	Estimate	Incidence Rate Ratio	Standard Error	Statistic	P-value
(Intercept)	2.40	11.00	0.30	7.95	0.00
connectivity_bin2	0.00	1.00	0.43	0.00	1.00
connectivity_bin3	0.69	2.00	0.37	1.88	0.06
connectivity_bin4	-0.45	0.64	0.48	-0.93	0.35
connectivity_bin5	0.17	1.18	0.41	0.41	0.68

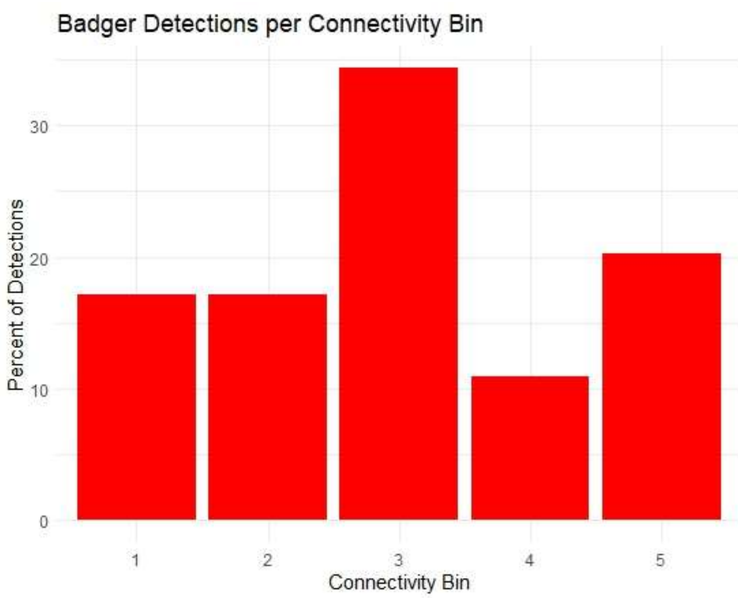

Figure 13: Percent of badger detections per structural connectivity bins where bin 1 has less movement potential and bin 5 has the highest movement potential.

Connectivity Categories

To aid in land use planning, we have categorized the structural connectivity model into channelized, diffuse (together representing 55% of the MDPC) and impeded (45% of the MDPC) categories for Municipal District of Pincher Creek (Figure 14). Channelized are areas where movement opportunity is restricted to a pinch point, and diffuse is where movement opportunity is widely dispersed. Impeded means animals may still move through these regions, but the habitat is less desirable as there are more anthropogenic features, or large water bodies. In the southwestern portion of the MDPC, rocky terrain and steep cliffs dominate the landscape, which are classified as impeded areas. For connectivity categories we restricted the assessment to the MDPC political jurisdiction.

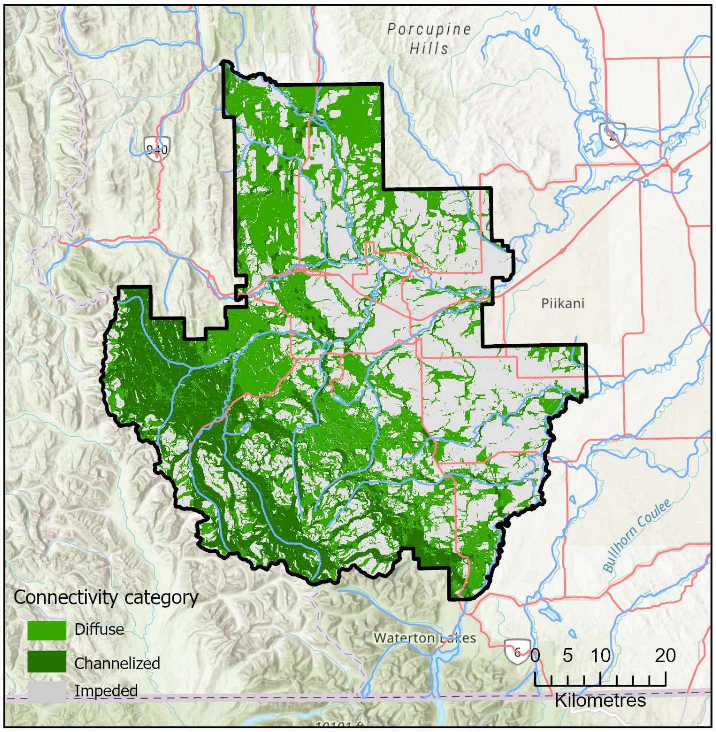

Figure 14: Structural connectivity categories in the MDPC, including diffuse (light green), channelized (dark green) and impeded (grey) in southwestern Alberta.

To aid in the development of strategies to maintain the ecological network we identified land management types for the diffuse and channelized connectivity categories (Figure 15). Crown other includes a diversity of GOA Ministries, such as Forestry and Lands, Transportation and Economic Corridors, Infrastructure, Tourism and Sport, and Energy and Minerals. Table 6 represents the square kilometers for diffuse and channelized connectivity.

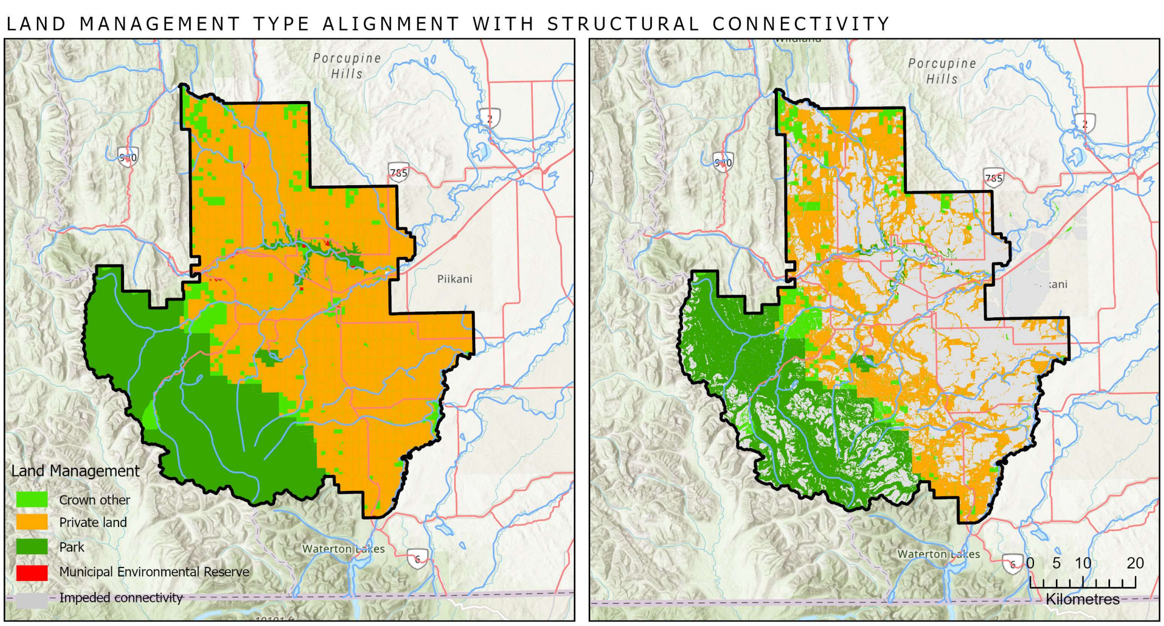

Figure 15: Map on the left represents land management type for the MDPC, while map on the right displays the land management types for diffuse and channelized connectivity in Southwestern Alberta.

Table 6: Percent of land per land management types in the MDPC in areas important for connectivity (diffuse and channelized). PLC refers to private land conservation.

Land Management Type	Km^2	% of MDPC
Park	770.6	40
Crown - other	208.5	11
Private non-PLC	713.9	37
Private PLC	241.6	12
MDPC	0.8	>1

To further aid strategy development, we considered municipal land use districts in relation to diffuse and channelized connectivity areas. Most lands are zoned as agriculture with less than one percent of land zoned for more intensive anthropogenic land use. Anthropogenic zoning include rural group county residential, hamlets, Castle Mountain Resort, landfill industrial, multi-lot heavy rural industrial, rural highway commercial, and urban fringe.

MDPC LAND USE DISTRICT ALIGNMENT WITH STRUCTUAL CONNECTIVITY

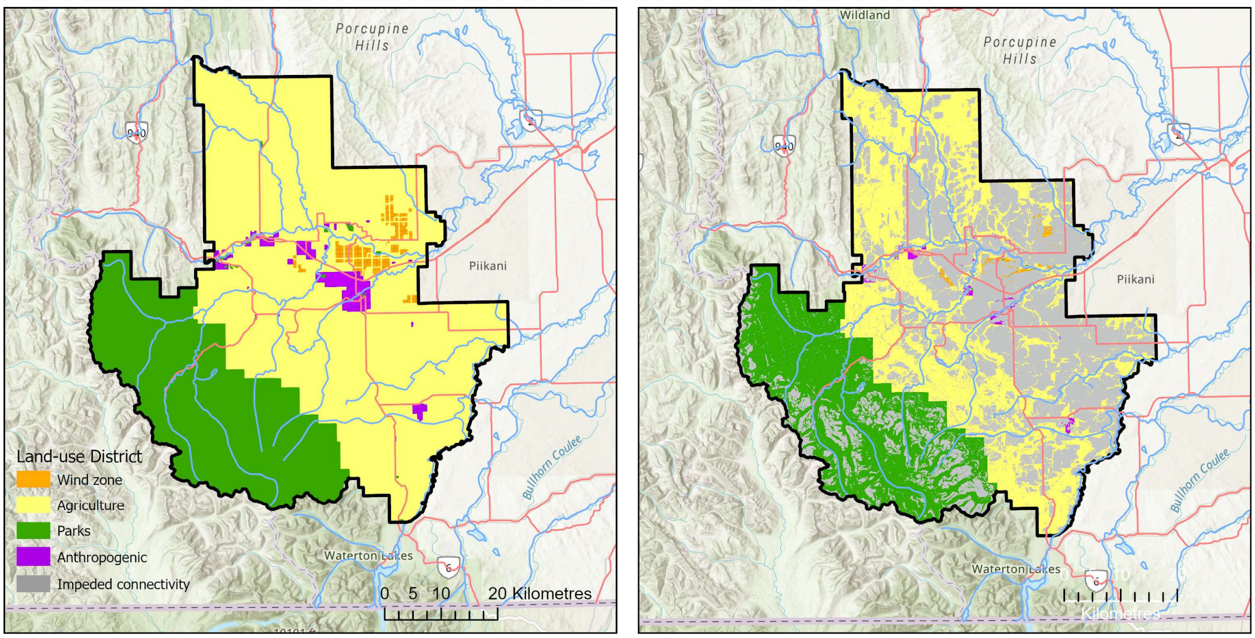

Figure 16: The map on the left represents land use districts for the MDPC, and the map on the right displays the land use districts for diffuse and channelized connectivity in MDPC.

Table 7: Percent of land per land use district in the MDPC in areas important for connectivity (diffuse and channelized) in the MDPC.

Land-use District	Km^2	% of the MDPC
Park	755.8	39
Anthropogenic	11.6	>1
Agriculture	1156.9	60
Agriculture/ wind energy	11.3	>1

Risk of Land Use Change

We identified land management type and assigned a development risk level (Table 8). Development risk was assessed based on legal land protection of a parcel. For example, private land conservation has a lower risk of development due to legally binding agreements, such as conservation easements, that permanently restrict land use. Provincial crown land owned by the Ministry of Forestry and Parks, on the other hand, have a higher risk of development due to the ministry's mandate for economic growth of wood products and forestry sector. We represent the landscape based on level of risk and per channelized and diffuse connectivity class to inform future strategy development with conservation practitioners.

Table 8: Risk to future land use change based on levels of protection

Ownership	Ownership category	Risk level
Private Land		
	Private land conservation	lower
	Private land	higher
Provincial		
	Protected Area/Park	lower
	Forestry	higher
	Grazing Lease	higher
	Others (transportation, tourism, culture, energy)	higher

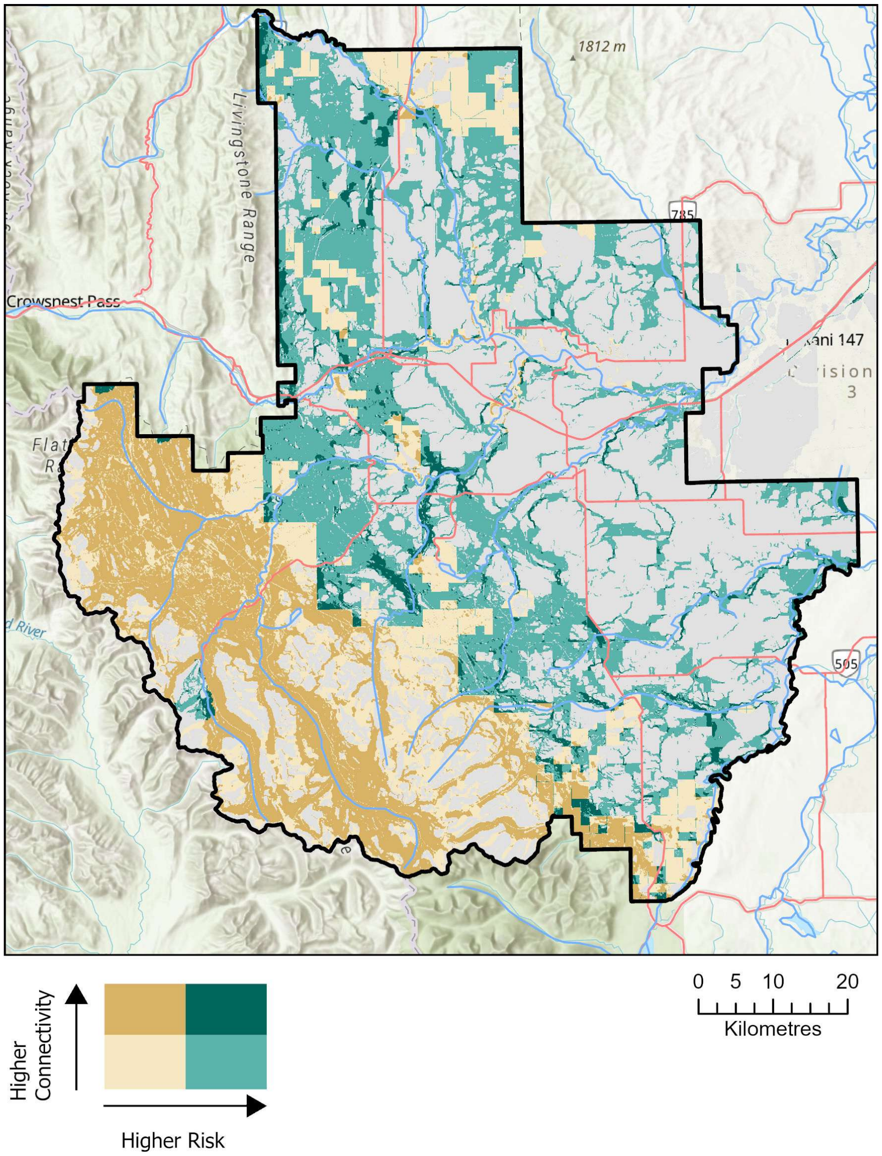

Figure 17: Lower and higher risk of anthropogenic land use change per connectivity category. Dark orange represents channelized higher risk areas and light orange channelized lower risk areas. Dark green represents diffuse higher risk areas and light green lower risk diffuse areas in the MDPC, Alberta.

Ecological Network Delineation

We identified core areas (40% of the MD) based on definitions outlined in table 8 as lands at lower risk from development. Then we identified corridors (36%) as remaining habitat from the structural connectivity model from channelized and diffuse connectivity categories. We identified 23% of the MD where movement is impeded. We refined the ecological network through a smoothing process (add and subtract buffer) and removed parcels not connected to a core area and those less than 10km^2 in size. As per the practitioner's workshop request, we display the core and corridors as the ecological network for display (Figure 18). Private Land conservation parcels were included in the percent calculations but are not displayed on the map.

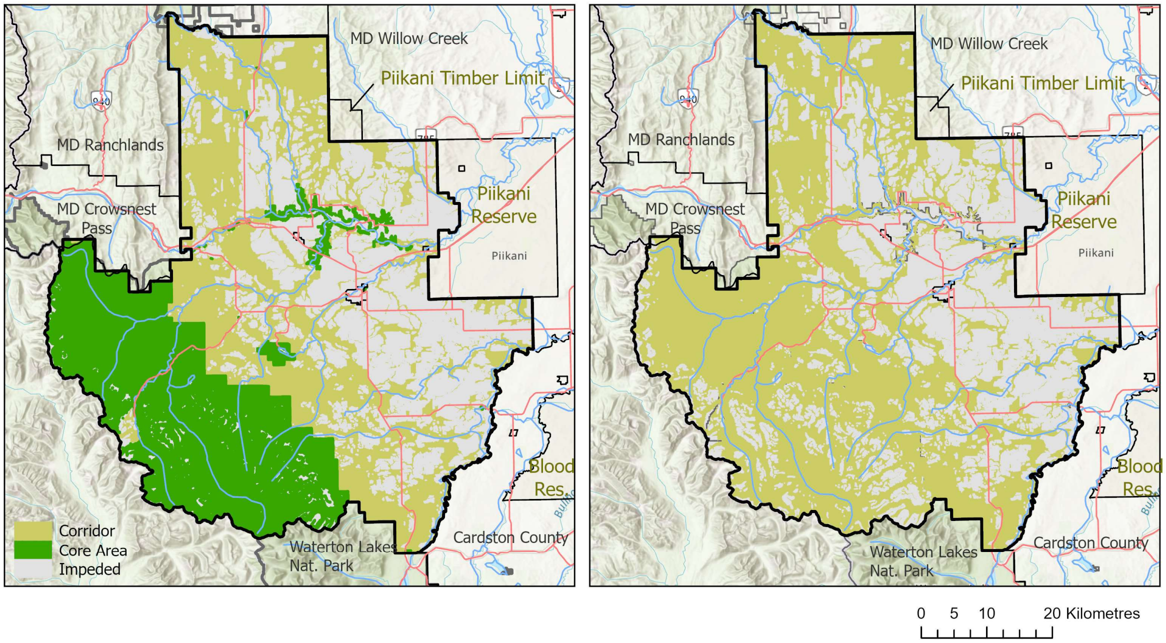

Figure 18: Ecological Network including core areas (in green) and corridors (light brown) to the left and ecological network on the right for Municipal District of Pincher Creek in Alberta Canada. Private land Conservation parcels have been removed from core area display.

Animal Vehicle Collision and Connectivity

We calculated an average of 367 AVCs per year (1,028 AVCs per year when a correction factor is applied) based on an average over five years along provincial highways in our study area. Deer species represent 83% of AVCs followed by striped skunk, elk and red fox (Table 9). Additionally, two species of conservation concern, grizzly bear and badger were reported in AVC data. Plots of species per year and total AVCs over the five-year period are displayed in Appendix A.

Table 9: Species involved in animal-vehicle collisions (AVCs) on provincial highway in the study area.

Species	AVCs per year	% of total AVCs
Mule deer	177.2	48.3%
White-tailed deer	124.8	34.0%
Striped skunk	13.2	3.6%
Elk	10.4	2.8%
Red fox	9.8	2.7%
Coyote	6.6	1.8%
Raccoon	5.4	1.5%
Moose	5	1.4%
Black bear	3.4	< 1%
Bighorn sheep	3.2	< 1%
Porcupine	2.8	< 1%
Badger	2.4	< 1%

Deer, Unknown	1.6	< 1%
Grizzly bear	< 1	< 1%
Beaver	< 1	< 1%
Bobcat	< 1	< 1%
Cougar	< 1	< 1%
Weasel, small species	< 1	< 1%

There were 16 statistically significant AVCs clusters in the study area. Statistically significant clusters are ranks from 0-16 in order of strength of which six of the sites (7, 9,10, 12, 14 and 16) are in the MDPC (Table 10, Figure 19)

Table 10: KDE + AVC cluster results and rankings of statistically significant clusters where cluster ID ranges from 1 (greatest strength) to 16 (lowest strength) along the provincial highway network in our analysis window.

Cluster ID	AVCs per Cluster	AVCs per Control Section	Cluster Strength	Str. Confidence Interval 1	Str. Confidence Interval 2
1	8	33	0.82	0.82	0.82
2	6	32	0.76	0.76	0.76
3	5	33	0.70	0.70	0.70
4	5	34	0.69	0.58	0.72
5	10	77	0.69	0.66	0.72
6	10	109	0.68	0.65	0.71
7	13	49	0.67	0.60	0.75
8	8	32	0.67	0.67	0.67
9	6	65	0.67	0.61	0.74
10	5	65	0.65	0.59	0.72
11	6	34	0.64	0.51	0.67
12	7	24	0.58	0.53	0.61
13	8	109	0.57	0.53	0.61
14	6	15	0.56	0.49	0.64
15	2	34	0.55	0.39	0.59
16	13	67	0.55	0.49	0.60

ANIMAL VEHICLE COLLISION CLUSTERS

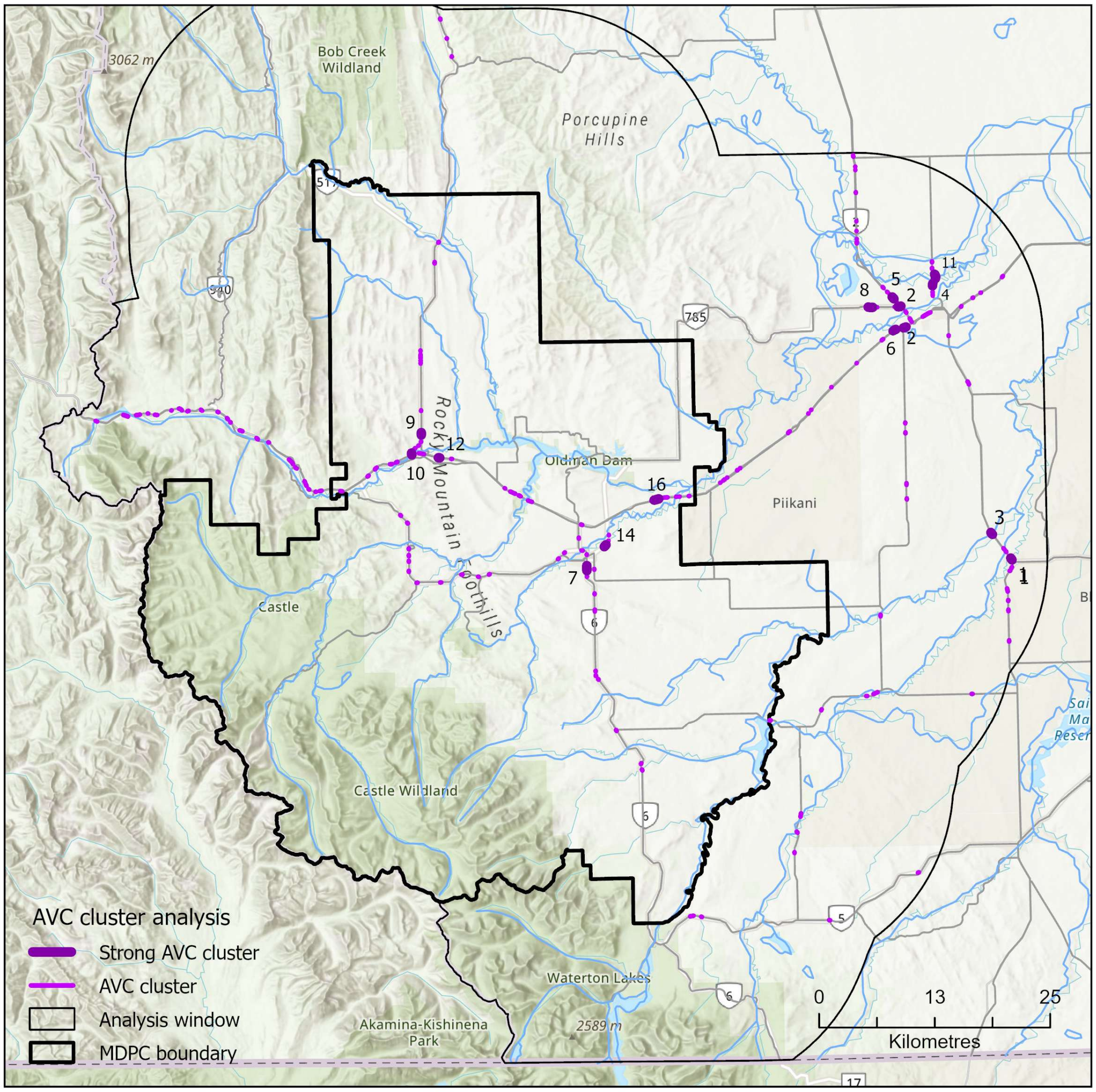

Figure 19: KDE + AVC cluster results and rankings of statistically significant clusters where cluster ID ranges from 1 (greatest strength) to 16 (lowest strength) along the provincial highway network in our analysis window.

We calculated the cost of collisions per km and determined the total cost of collisions in the analysis window as approximately $19,025,407 CDN per year. Using the AWW Program approach whereby all AVC are assigned a value of $100,000 CDN, the total cost of collisions is approximately $30,280,000 CDN per year. A breakdown of AVC costs/km is displayed in Figure 20.

AVC COST PER KM

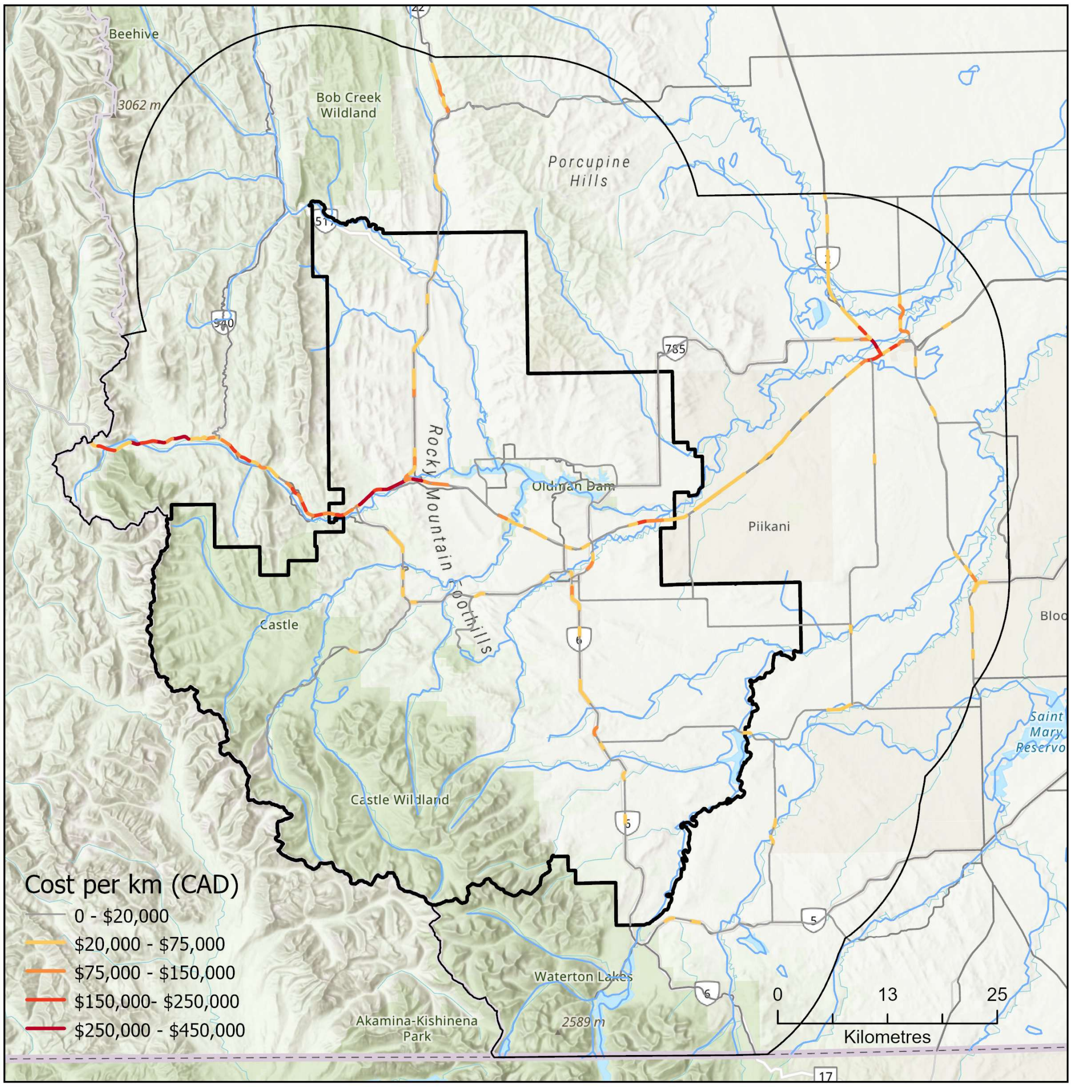

Figure 20: Annual AVCs per kilometer based on five-year average along the provincial highway network in our analysis window. The analysis window is displayed in thin black line, while the MDPC is a thick black line.

We identified 30 km of provincial highway network in the MDPC where there is a strong alignment between motorist safety risk and structural connectivity (Figure 21). The alignment between AVC and connectivity value index is displayed in a quadrant plot in Appendix A.

AVC AND STRUCTURAL CONNECTIVITY ALIGNMENT

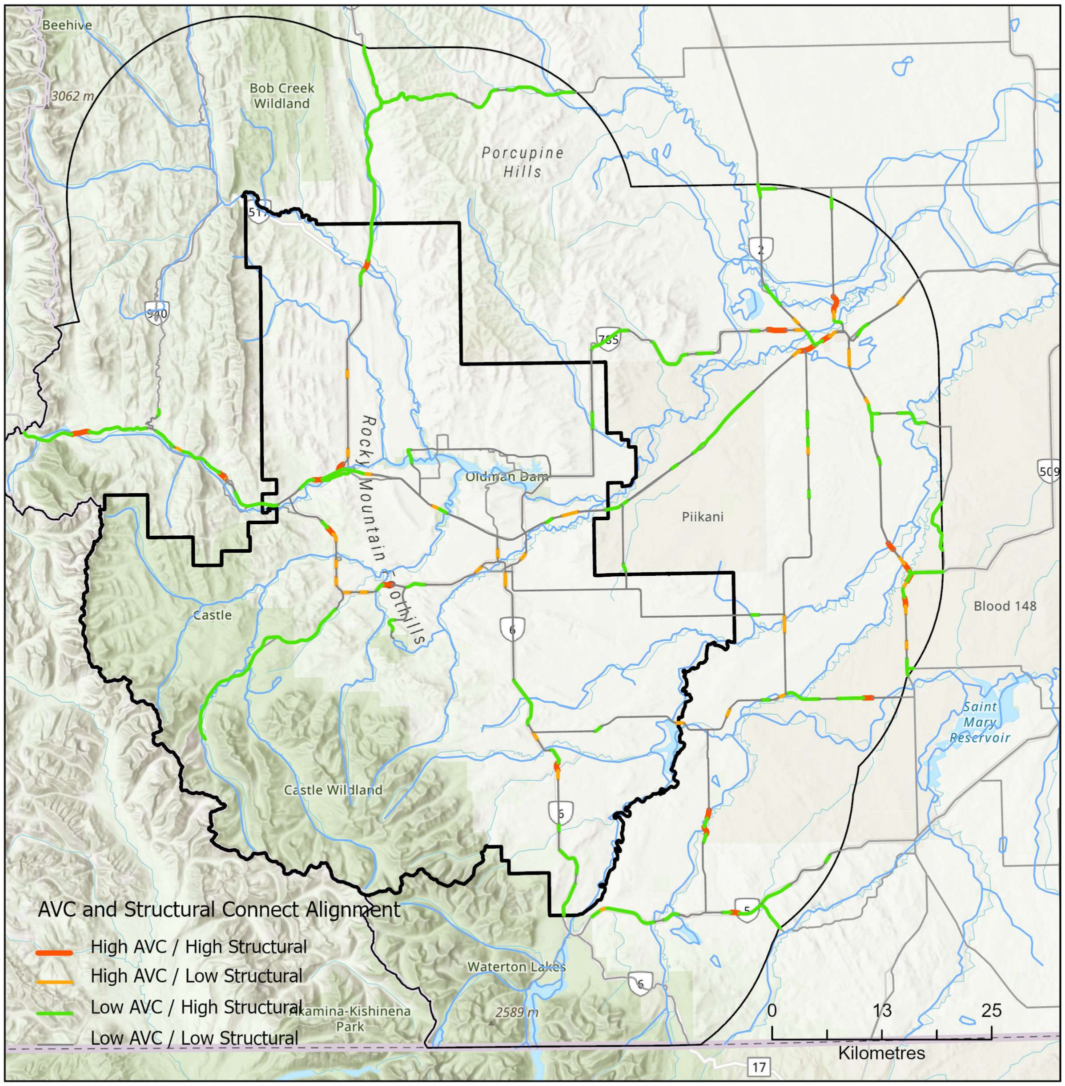

Figure 21: AVC (based on index generated from KDE+ clusters) and structural connectivity (based on index generated from mean value of structural connectivity values) per km in analysis window.

Practitioners Workshop

We held a workshop on May 2, 2025 with 17 conservation practitioners to review the structural connectivity models and validation process and to identify key strategies toward the protection of an ecological connectivity network. Participants were guided through an online workspace using the collaboration platform, MIRO, with spatial maps to facilitate discussion. As an initial step participants reviewed the structural model and core areas and provided the following feedback:

- Consider renaming core areas to habitat patch or intact landscapes to avoid confusion with grizzly bear core areas.
- The habitat patch spatial product was missing key areas.
- There was some concern that the size threshold of 13 km^2 was too large to capture some smaller but important areas.
- Consider displaying ecological connectivity around the Municipal District of Pincher Creek to provide context and help to identify linkages between jurisdictions.

- Review structural connectivity in relation to riparian areas and add riparian setbacks if not included in structural model.
- Simplify the network to be displayed on a map as one layer when sharing with public and planning.
- Consider showing areas that can be developed – flip the structural model.

Participants felt the categorization of channelized to diffuse were helpful for strategy development.

We reviewed Crown lands jurisdiction in relation to important connectivity areas and participants noted the need to engage with multiple Ministries responsible for land management of important parcels, including Environment and Protected Areas, Forestry and Parks, Transportation and Economic Corridors, Tourism and Sport, Agriculture and Irrigation, and Energy and Minerals. Participants noted that some of the Crown parcels managed by Tourism and Culture have been identified for new recreational infrastructure which may conflict with purpose of the ecological network. Key recommendations from the workshop included exploring and adding the ecological network to the provincial reservation system [1] which can limit certain types of activities and into the Landscape Analysis Tool. There was also a recommendation to understand how an update of the Master Schedule of Standards and Conditions, which identifies conditions that apply to formal disposition applications approved under the Public Lands Act, could incorporate an ecological network for the consideration of dispositions to Forestry and Parks and Alberta Energy Regulator who manages public lands in Alberta. Lastly, it will be important to follow up with Tourism and Sport and the All-Seasons Resort Act as the Castle Mountain Area has been identified as a Tourism Designation Zone which could bring an increase in visitation and tourism to the region. This area may also be identified as a candidate for the Alberta's All Season Resort Act.

For municipal governance it was noted there is currently language in the Municipal District of Pincher Creek's (MDPC) Municipal Development Plan (MDP) to support ecological connectivity, but a map is not currently included. Ideally, an ecological network map would be included in the MDP. Participants recommend that we display core and corridors as one layer called wildlife movement areas. The ecological network should also be integrated into the area structure plans and land use by-laws to facilitate implementation. It was noted that the wildlife movement tool and ecological connectivity overlay policy developed for Municipal District of Crowsnest Pass will be expanded to the MDPC.

As a large portion of the MDPC is privately owned land, participants recommended coordinating with the private land conservation community to identify priority lands for protection and stewardship and clearly outline incentives for landowners associated with important connectivity areas. We could use channelized connectivity areas that are at higher risk to development as a starting point for further discussions. Participants noted the new Land Trust Grant Program Framework designed to support private landowners who maintain ecological goods and services. It was recommended we understand how ecological connectivity could be incorporated into this new framework. Lastly, the MDPC has a green acreage guide provided to new landowners which could incorporate language on the ecological network.

Participants noted the importance of engaging with Indigenous communities.

Based on the workshop discussion we outlined five strategy approaches: integration with planning and policy at provincial and municipal level, conservation incentive programs for private landowners, transportation and infrastructure mitigation (such as wildlife crossing structures), public lands management and Indigenous-led stewardship.

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[1] A reservation or Crown land reservation means a record within the public land registry that identifies and provides notice to users that a specified management intent as supported by policy and government programs applies to a parcel of Crown land.

Discussion

Structural connectivity as representative of terrestrial animal movement

We used a structural connectivity model to form the basis of an ecological network for terrestrial large mammals in the Municipal District of Pincher Creek. Structural connectivity focuses on the physical layout of habitats and the arrangements of landscapes, while functional connectivity refers to how these structures facilitate or hinder wildlife movement (Brodie et al., 2025). The relationship between structural connectivity and the movement of large terrestrial animals is an area of increasing research interest, particularly in the context of landscape ecology and conservation. We identified a structural approach that has been demonstrated by other research to inform regional land use planning(Marrec et al., 2020). Our assumption is that structural connectivity represents geographically important movement areas for terrestrial mammals.

We tested if the structural connectivity model spatially represented movement of several terrestrial mammal species by testing connectivity against an elk movement dataset, and moose, grizzly bear, black bear and badger occurrence records. Our results highlight the value and complexity delineating an ecological network using structural connectivity. Elk and moose were well represented in areas with higher connectivity value (represented as bins 3-5), including in five different movement types for elk. Elk movement data indicates activity within the structural connectivity model varied geographically depending on the season (winter and summer) or movement types including migration, dispersal and residence animals. These results are similar to a study on bison in Saskatchewan that concluded structural connectivity (the physical arrangement of meadows and forests) depicted movement opportunity, but functional connectivity was shaped by bison's seasonal habitat preferences and movement rules, demonstrating that animal spatial dynamics depend on behavioral decisions that vary across time and scale (Dancose et al., 2011). For ungulates in our study area, high structural connectivity value (represented as bins 3-5) represented movement needs well.

Species that exhibit movement influenced by behavioral responses to human altered landscape features such as grizzly bear, black bear and badger were not as well represented by the structural connectivity model. Grizzly bear occurrences were well represented in high structural connectivity areas, but the second most common number of detections were in the lowest structural connectivity areas. The lowest connectivity areas represent more disturbed landscape and include agricultural attractants such as deadstock composting piles, calving grounds, palatable crops, grain bins, and silage. We used a combination of rub tree grizzly bear occurrences (Morehouse & Boyce, 2016) and FWMIS data. The FWMIS data may be biased to conflict reporting and hence over-represent areas with attractants that lead to conflict. Grizzly bears are attracted to these food sources, often resulting in movement through disturbed portions of the landscape. Grizzly bears are also sensitive to human activity levels (not incorporated into structural connectivity models) and may alter their use of good habitat to avoid human activity (Palm et al., 2023). Black bear occurrences also were most frequently detected in lower structural connectivity value areas. Black bear research from the area noted that black bear density and structure was impacted by land tenure with bears density higher in protected areas and lowest on crown lands (non-protected)(Loosen et al., 2019). In addition, badger occurrences did not have a statistical relationship to structural connectivity, which may be expected because badger will utilize low structural connectivity value pasture lands and croplands. Badger occurrences were from FWMIS dataset and likely from wildlife assessments relating to wind energy development resulting in bias dataset to specific development type.

Current research indicates while structural connectivity provides a good framework for understanding habitat arrangements, it is also essential to incorporate insights of animal behavior and ecological processes into connectivity modeling(Fattebert et al., 2015; Ghoddousi et al., 2021). We recommend future phases of research consider functional connectivity species-specific models, which include animal behavior to improve landscape management strategies for the movement of large terrestrial species. However, structural connectivity modelling is an important starting point for retaining current natural connections in land use planning and decision-making (Marrec et al., 2020).

Classification of structural connectivity into connectivity categories, land management type, and road sections.

A key challenge for developing conservation strategies for ecological connectivity is the abstract nature of connectivity products, usually represented as low to high connectivity values across a spectrum. To inform development of conservation strategies to maintain or restore ecological connectivity in the MDPC we categorized the structural connectivity model into three connectivity categories (channelized, diffuse, and impeded) based on connectivity bin structure and results from the validation process (Cameron et al., 2022). Connectivity categories, signifying where terrestrial mammal movement is pinched or is more flexible, enables practitioners to better operationalize conservation strategies. For example, workshop practitioners identified channelized areas as important for direct protection or for integration into planning and policy since a change in land use may impede future mammal movement. In diffuse (non-pinch point) connectivity areas, suggested strategies will focus on promotion of stewardship projects such as wildlife friendly fencing. In some cases, it was noted that although flow rates tend to be higher in channelized areas, movement in diffuse areas may be more important to maintain. Channelized areas are comprised of constricted flow rates and may be an artifact introduced by the modeling approach (Morrison & Reynolds, 2010).

We also displayed channelized and diffuse areas per landowner type, such as private land, provincial Crown lands, and provincial and municipal parks to better operationalize conservation actions. In our study area, 51% of channelized or diffuse connectivity areas are managed by the Government of Alberta (GOA), emphasizing the importance of provincial support and engagement in connectivity science and conservation. Furthermore, of the GOA jurisdiction, 40% is designated as a park, with the remainder under one of many different provincial government ministries, including Transportation and Economic Corridors, Energy and Mining, Forestry and Parks, Environment and Protected Areas, and Tourism and Sport. This highlights the need for better integration of connectivity within GOA between ministries. Conservation practitioners outlined knowledge gaps, such as approaches to land management of parcels managed by the different provincial ministries.

The remaining 49% of channelized and diffuse connectivity areas are held by private landowners, of which 12% is owned by conservation organizations or has a conservation easement on the land title. In total 52% of channelized and diffuse connectivity areas are at lower risk from development due to some level of protection. Conservation practitioners recommended remaining private lands aligning with channelized and diffuse connectivity areas should focus on voluntary incentive programs to promote protection of existing connected areas and to improve terrestrial mammal movement.

We also reviewed the MDPC zoning to identify potential conflict with diffuse and channelized connectivity types and municipal zoning. A key finding here is 40% of diffuse and channelized areas are zoned as park and 60% as agriculture. Currently existing municipal zoning is conducive to supporting maintenance of diffuse and channelized areas. Conservation practitioners stressed the importance of conservation strategy approaches that use voluntary landowner incentives to promote co-existence on agricultural-zone areas. There was also a recommendation to review Area Structure Plans (ASP) in relation to the ecological network to ensure terrestrial mammal movement is not compromised.

An important conservation strategy is to assess where terrestrial mammal movement intersects the highway network to inform implementation of wildlife crossing structures and funnel fencing to improve both movement and motorist safety (Boyle et al., 2017; Ford et al., 2011; Glista et al., 2009; Lee et al., 2023; Rytwinski et al., 2016; Teixeira et al., 2017). Within the MDPC there were six statistically significant AVC clusters that meet the threshold for GOA to consider road mitigation to improve motorist safety (Alberta Transportation and Economic Corridors, 2023a). But AVC sites are driven by deer-vehicle collisions and may not meet the movement needs of other terrestrial mammal species. We identified 30 kilometers of the provincial highway network where high structural connectivity flow aligned with the AVCs clusters.

By mapping connectivity into distinct categories and examining these categories by land management type and municipal zoning, we identified five key conservation strategies (Keeley et al., 2019):

1. Integration of connectivity into provincial and municipal planning and policy
2. Conservation incentive programs for private landowners
3. Transportation and infrastructure mitigation
4. Public lands management
5. Indigenous-led stewardship

These strategies will be discussed in the MDPC connectivity conservation action plan, which will outline collaboration conservation actions to maintain and improve terrestrial mammal connectivity on the landscape.

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Appendix A: Animal Vehicle Collision (AVC) plots

*Using Alberta Wildlife Watch dataset, we plotted total number of collisions per year (Figure 22), species involved in collisions per year (**Error! Reference source not found.**) and AVCs per month (Figure). We display collision mortality locations for two species of conservation concern, grizzly bear and badger (). The quadrant plot used to identify where alignment between AVC clusters and connectivity value per road section is displayed in Figure 25:Species at Risk AVC locations for grizzly bear (red) and badger (orange) in MDPC and surrounding area.*

Figure 26.

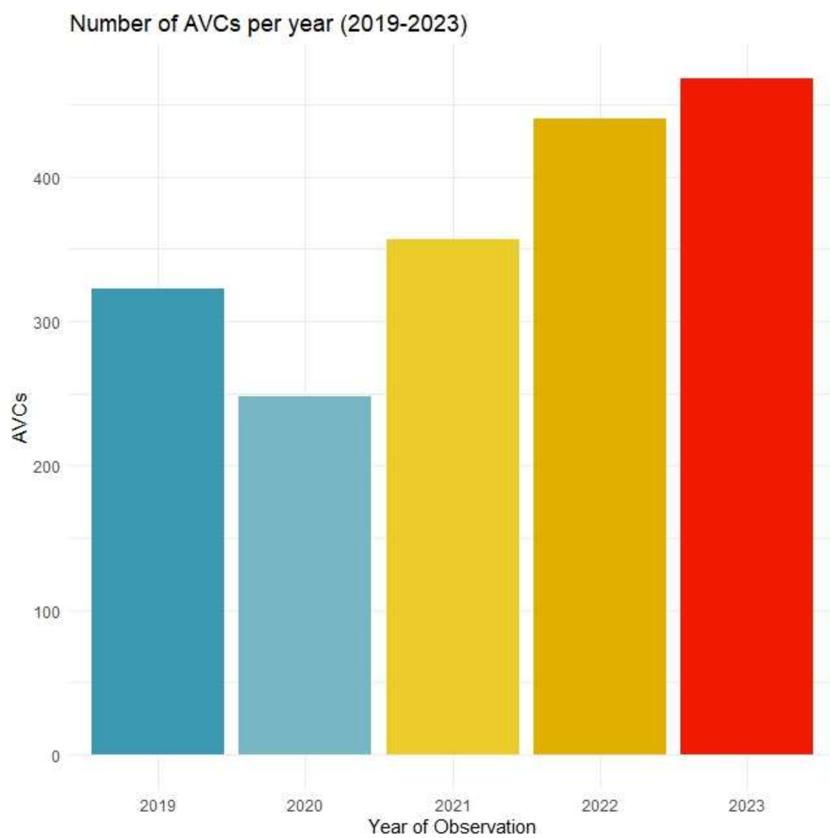

Figure 22: Total AVCs per year over five-year study period for provincial highway network in Pincher Creek.

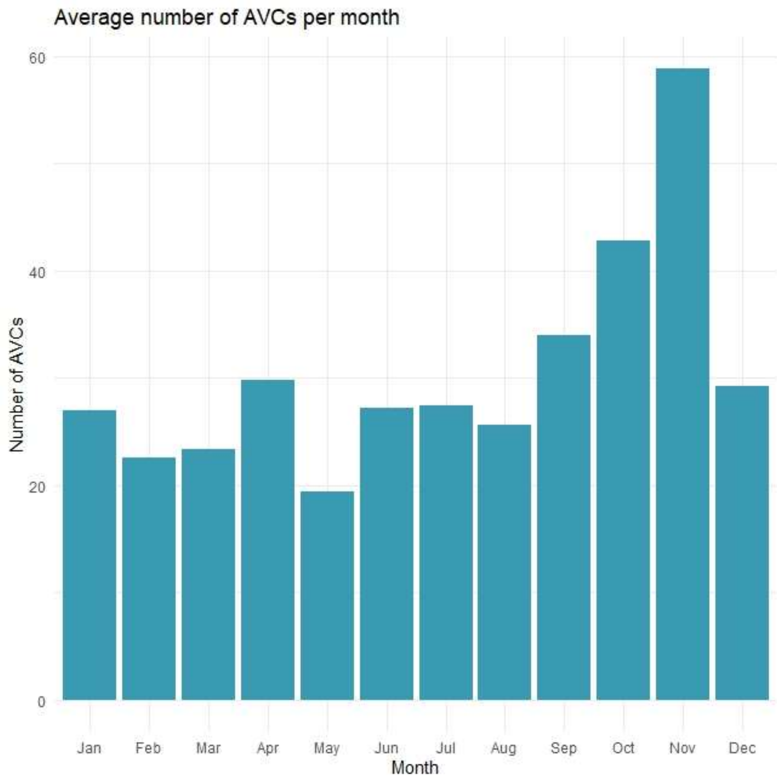

Figure 23: Average annual AVCs per month over five-year study period for provincial highway network in Pincher Creek.

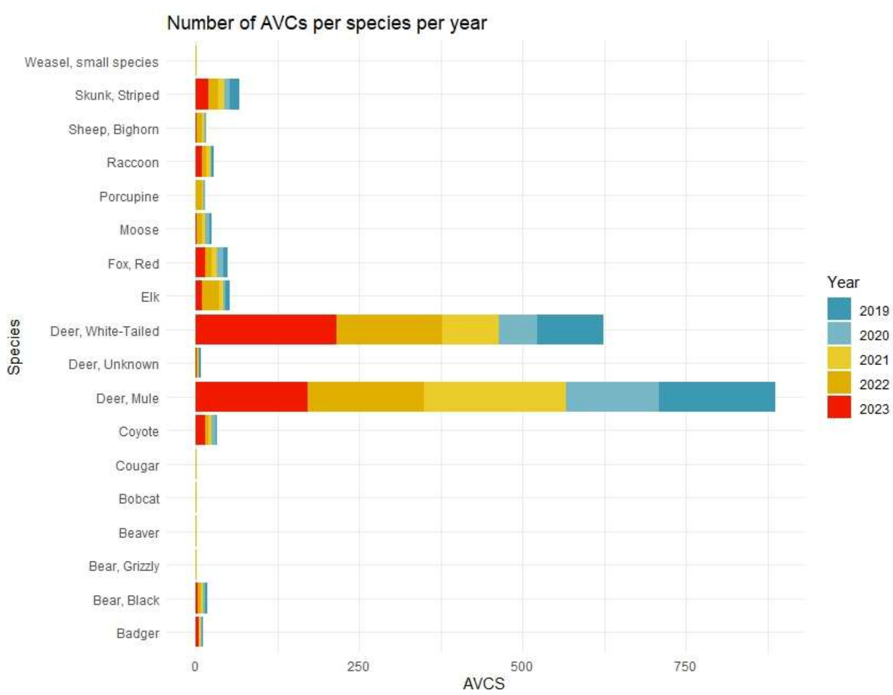

Figure 24: Animal Vehicle Collisions by species reported to Alberta Wildlife Watch program from 2018-2023) in the MDPC and surrounding area in Alberta.

AVC FOR SPECIES OF SPECIAL CONCERN

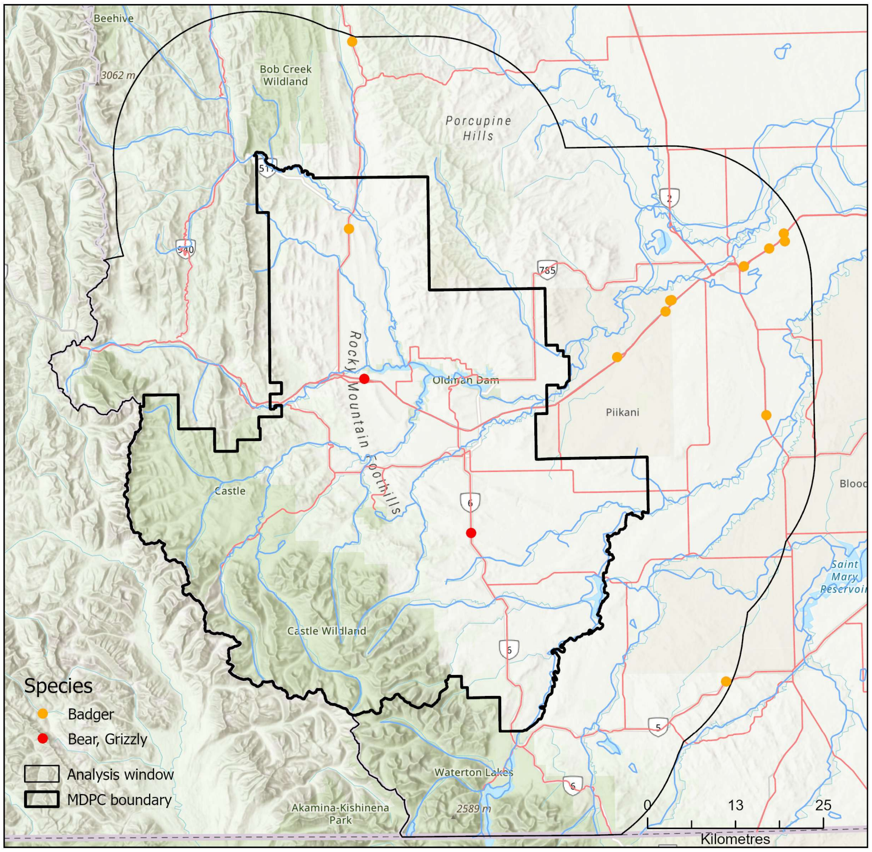

Figure 25:Species at Risk AVC locations for grizzly bear (red) and badger (orange) in MDPC and surrounding area.

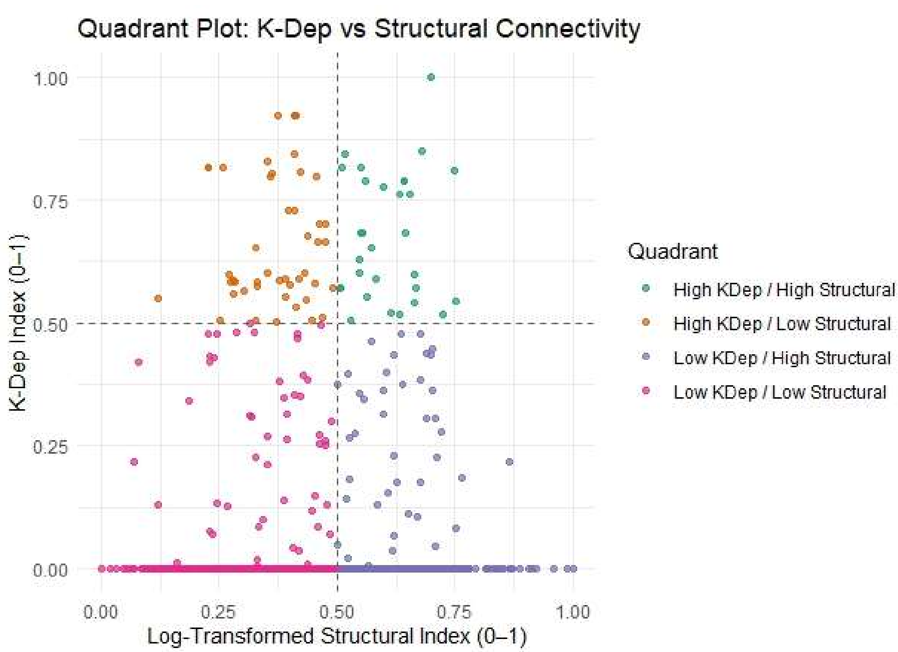

Figure 26: Quadrant plot for AVC and connectivity value indexes

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