ALBERTA BIODIVERSITY INDICATORS

Landscape Connectivity Indicator for Alberta

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Summary

Canada is a party to the UN Convention on Biological Diversity, which identifies the conservation and restoration of biological diversity as a global priority. The Kunming-Montreal Global Biodiversity Framework, adopted at the 15th Conference of the Parties (COP15) to the United Nations Convention on Biological Diversity in 2022, defines biodiversity conservation and restoration goals and targets. Provinces and territories need to monitor and track progress towards these goals and targets. Alberta Environment and Protected Areas and the Alberta Biodiversity Monitoring Institute (ABMI) jointly developed a series of provincial indicators to estimate the status of biodiversity in the province. Among these indicators, Landscape Connectivity is an important indicator that quantifies the degree of connectivity of natural habitat patches. The indicator can be applied at different spatial scales, from the entire province to a local area where input data are available.

The Landscape Connectivity indicator captures information about the amount of undisturbed landcover and its configuration across the landscape. An Equivalent Connected Area index was selected to measure landscape connectivity and assess changes in landscape connectivity over time. The indicator accounts for three broad landcover types: Upland Forest, Lowland Forest (including bogs, fens, swamps, and marshes), and Grass-Shrub. Landscape connectivity of these broad habitat types, as well as an aggregated landscape connectivity, were calculated for all Hydrological Unit Code 8 (HUC 8) watersheds in Alberta for 2010, 2018, 2019, 2020, and 2021 using four GIS layers:

- Human Footprint Inventory (HFI),
- ABMI Wall-to-Wall Vegetation Layer Including “Backfilled” Vegetation (Version 7.0),
- Wildlife crossing locations in National Parks, and
- Hierarchical Watershed Boundaries of Alberta.

The Landscape Connectivity indicator dataset is available on GeoDiscover Alberta (Landscape Connectivity Indicator for Alberta).

Contents

1. Introduction

Landscape connectivity represents the degree to which landscape composition (including both native (i.e., natural) and anthropogenic (i.e., human-caused) disturbances) and configuration impact the ability of organisms to move between suitable habitat patches (Taylor et al., 1993; Blake and Baarda, 2018). There are three main approaches for quantifying landscape connectivity (Calabrese and Fagan, 2004):

- **Structural connectivity:** This can be determined from physical attributes in the landscape, and based on maps alone (i.e., without reference to movement behaviour of a single species).
- **Potential functional connectivity:** This is determined using assumptions on organismal movement behaviour (e.g., by mapping a single species' habitat and setting dispersal thresholds).
- **Actual functional connectivity:** This is determined using observed data (e.g., species occupancy, radio tracking, mark-recapture, or molecular genetic data), which reflect actual rates of the exchange of organisms (or genes) among habitat patches.

Our Landscape Connectivity indicator uses the structural approach for quantifying landscape connectivity and thus relies on evaluating the impacts of anthropogenic disturbances in the landscape, and the approach is species agnostic (i.e., does not account for ecological or biological requirements of species). Anthropogenic disturbances have resulted in a fragmented landscape with patches of native habitat and human development (footprint). Fragmentation of native habitat into many patches decreases its connectivity and increases patch isolation (Forman, 1995; Jaeger, 2000; Ernst, 2014). Decreased connectivity and isolation of the remaining native habitat can have direct and indirect negative effects on species richness, biodiversity, ecosystem function and the provision of ecosystem services (Mitchell et al., 2013; Roch and Jaeger, 2014). Landscape-level processes such as species movement, foraging, dispersal, genetic connectivity and meta-population dynamics all depend on connectivity of natural habitat and the ability of organisms to move through the landscape (Forman, 1995). Appendix 1 provides a detailed review of landscape connectivity.

An Equivalent Connected Area (ECA) index is selected as the metric for the Landscape Connectivity indicator. Landscape connectivity is calculated for three broad habitat types: Upland Forest, Lowland Forest, and Grass-Shrub, and an aggregated landscape connectivity is also calculated.

There are five key parameters for calculating the ECA index:

- Dispersal distance: 250 m, representing how far a species can disperse.
- Cost distance: 1 to 10, representing a scale for how difficult it is for species to move through the landscape.
- Minimum viable patch size: one hectare, minimum size of a patch for it to be considered viable for multiple species.
- Reference condition: landscape condition without any human footprint.
- Recovery of forest harvest areas: harvest areas recover over time, with full recovery achieved at 80 years post harvest.

2. Landscape Connectivity Indicator

2.1 Indicator intent

The intent of the Landscape Connectivity indicator is to measure and track the connectivity of three broad habitat types compared to the state of the landscape in the absence of human footprint (reference condition). This indicator quantifies the amount of undisturbed landcover and its configuration on the landscape across the province of Alberta.

The Landscape Connectivity indicator accounts for three broad landcover types: Upland Forest, Lowland Forest, and Grass-Shrub. These are the dominant habitat types that broadly represent different Natural Regions within the province (Natural Regions Committee, 2006). Streams and rivers were not considered as habitat types for this indicator as there are alternative methods for assessing connectivity in those systems (Diebel et al., 2015; Alberta Environment and Protected Areas, 2022).

2.2 The data

The following four GIS layers were used to calculate the indicator:

- Human Footprint Inventory (HFI)
- ABMI Wall-to-Wall Vegetation Layer Including "Backfilled" Vegetation (Version 7.0)
- Wildlife crossing locations in National Parks
- Hierarchical Watershed Boundaries of Alberta.

Human Footprint Inventory (HFI)

This is a provincial scale GIS layer created and maintained by the ABMI through the Alberta Human Footprint Monitoring Program (AHFMP) that consolidates 115 types of anthropogenic disturbance into 20 subcategories (Alberta Biodiversity Monitoring Institute, 2020). AHFMP is a collaboration between the Government of Alberta and the ABMI aimed to produce accurate and up to date provincial human footprint data. This layer allowed us to determine the loss of native habitat due to anthropogenic disturbances. It differentiates harvest areas, which are predicted to recover over time, from other types of anthropogenic disturbances.

ABMI Wall-to-Wall Vegetation Layer Including "Backfilled" Vegetation

This is a provincial scale GIS layer that tracks the current vegetation, habitat, soil, and anthropogenic disturbances (Alberta Biodiversity Monitoring Institute, 2017). This layer allowed us to assign habitat types (Upland Forest, Lowland Forest, and Grass-Shrub) and stand types for harvest areas which can be used to incorporate forest recovery curves for deciduous and coniferous stands (see Section 2.4.5). In addition, this layer provides information on the landcover types present prior to disturbance (i.e., backfill layer) which is used to determine the reference condition. We used version 7.0 of the backfill layer for this indicator, though the documentation hasn't been publicly released. Therefore, we are citing the previous version of this data layer.

The backfill layer habitat information was simplified into three broad habitat types: Upland Forest, Lowland Forest, and Grass-Shrub (Table 1). Upland Forest includes various upland forest types (coniferous, deciduous and mixedwood forests), Lowland Forest includes wetlands (treed and shrubby fens, bogs, swamps), and Grass-Shrub represents grass and shrub habitats in southern Alberta (Figure 1). Two other native landcover types (Bare Ground and Open Water) were also assigned using the backfill layer. However, we did not calculate landscape connectivity for these habitat types.

Table 1. Lookup table for aggregating the habitat categories from the ABMI backfill layer into broad habitat types.

Backfill Layer Habitat	Broad Habitat Type
Alkali	Grass-Shrub
GrassHerb	Grass-Shrub
Shrub	Grass-Shrub
GraminoidFen	Lowland Forest
Marsh	Lowland Forest
ShrubbyBog	Lowland Forest
ShrubbyFen	Lowland Forest
ShrubbySwamp	Lowland Forest
TreedBog-BSpr	Lowland Forest
TreedFen-BSpr	Lowland Forest
TreedFen-Decid	Lowland Forest
TreedFen-Larch	Lowland Forest
TreedFen-Mixedwood	Lowland Forest
TreedSwamp-Conif	Lowland Forest
TreedSwamp-Decid	Lowland Forest
TreedSwamp-Fir	Lowland Forest
TreedSwamp-Mixedwood	Lowland Forest
TreedSwamp-Spruce	Lowland Forest
TreedSwamp-Forest	Lowland Forest
TreedWetland-Mixedwood	Lowland Forest
Decid	Upland Forest
Mixedwood	Upland Forest
AlpineLarch	Upland Forest
Conif	Upland Forest
Fir	Upland Forest
Pine	Upland Forest
Spruce	Upland Forest
Bare	Bare Ground
SnowIce	Open Water
Water	Open Water

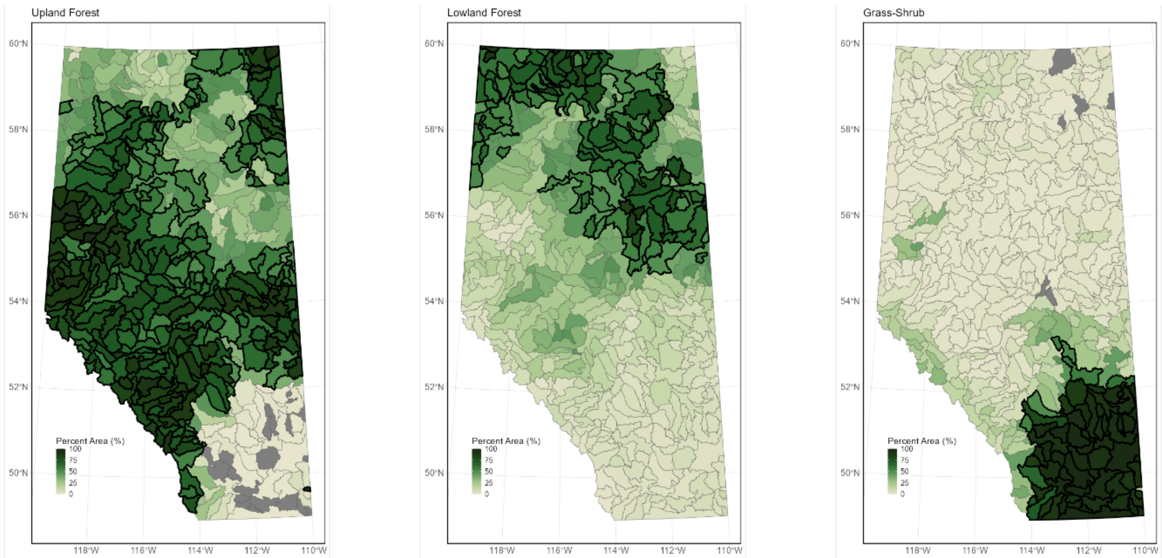

Figure 1. Percent areas of the three habitat types: Upland Forest (left), Lowland Forest (centre), and Grass-Shrub (right) within each HUC-8 watershed under the reference condition. Watersheds outlined in black represent the watersheds where Upland Forest, Lowland Forest or Grass-Shrub are the dominant habitat type. Watersheds where a habitat type was not observed under reference conditions are colored in grey.

Wildlife crossing locations in National Parks

A dataset on wildlife crossing locations was provided by Parks Canada that included information about where crossing infrastructures, such as overpasses and box culverts, occur in National Parks. This type of infrastructure can facilitate movement between habitat patches, reducing the impact of road development on connectivity. For example, a literature review on the effectiveness of overpass crossings found that species such as deer, black bears, moose, and other medium-large mammals actively use these crossings to move between habitat patches (Brennan et al., 2022). We applied a 100-m buffer to each crossing location and inspected each buffer to make sure that the neighboring native habitat patches were connected by the buffer. Wildlife crossings located outside the National Park system will be incorporated in future updates to this indicator.

Hierarchical Watershed Boundaries of Alberta

The Hydrologic Unit Code Watersheds of Alberta is a nested hierarchically structured drainage basin feature classes that was developed by the United States Geological Survey (USGS) with accommodation to reflect the pre-existing Canadian classification system. It allowed us to aggregate the status of landscape connectivity based on ecologically relevant boundaries.

2.3 The Equivalent Connected Area (ECA) metric

Fiera Biological Consulting (2019) conducted a detailed review of four potential approaches and associated metrics for assessing landscape connectivity (Appendix 1). Upon review of the Fiera report, we chose to adopt the Equivalent Connected Area (ECA) index as the measure of landscape connectivity. The ECA index takes the spatial distribution of a habitat and determines the size of a single habitat patch that would provide an equivalent amount of connectivity as a unit of area (Saura et al., 2011).

For example, two native habitats, each one hectare in size, would be equivalent to a single patch two hectares in size if there were no barriers to connectivity. The maximum value for the indicator is equal to the area of an analysis region, assuming it is 100% native habitat. This index is based on a Graph Theory framework and includes variables such as patch size, the dispersal abilities of organisms, and the impacts of landcover and human footprint on dispersal ability (i.e., cost distance).

The ECA index has three main components, with the variables described in Table 2:

1) $ECA = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i \, a_j \, p_{ij}}$
2) $p_{ij} = \exp\,(k \times distance \times cost)$
3) $k = \log(0.05)\,/250$

Table 2. Definition of the variables used in the ECA index.

Variable	Definition
a_i	Area of patch *i*
a_j	Area of patch *j*
n	Number of patches in an analysis unit (HUC-8 watershed)
p_{ij}	Maximum probability of connection between patches *i* and *j*
k	A constant that determines decay of negative exponential function, defined by the dispersal distance (250 m).
distance	Euclidean distance between edges of patches *i* and *j*
cost	Mean cost of moving through the landscape matrix (anthropogenic and natural features) for the region.

The ECA index was calculated for each of the three habitat types in HUC-8 watershed units. These scores were then area-weighted to generate an aggregated indicator value for each watershed. The areas used for weighting the ECA index across habitat types were based on the amount of habitat available in the reference condition (see Section 2.4.4). By calculating connectivity for each HUC-8 watershed, our understanding of future impacts to connectivity is restricted to developments within the watershed. Due to this restriction, this indicator does not consider impacts of adjacent or extending human footprints from HUC-8 units surrounding the watershed summary unit.

A benefit of the ECA index is that it can be reported in both unit areas (e.g., km^2) as well as a percentage when comparing to the reference landscape condition. This allows us to facilitate interpretation and communicate results to stakeholders, while having the ability to create standardized management targets across regions of interest (e.g., target of 80% connectivity).

2.4 Key parameters

There are five key parameters which influence how the ECA index will respond to land-use change. Two of the parameters (dispersal distance and cost distance) are variables defined in the index calculation. The other three parameters (minimum viable patch size, reference condition, and recovery of forest harvest areas) influence the sensitivity of the indicator, which demonstrate how connectivity changes with the recovery of harvested areas and isolating the impacts of human disturbance on landscape connectivity.

2.4.1 Dispersal distance

Different species have different dispersal capacities and thus different dispersal thresholds (e.g., maximum reachable distance within habitat). As a species' dispersal capability increases, the ECA index converges with the proportion of available native habitat (Figure 2). In contrast, for small dispersal distance the ECA index will approach zero as species will be unable to move across even the smallest disturbances. Nevertheless, from an ecological perspective, some species may have very small dispersal distances and could still move very short distances in the landscape. However, from an application perspective, if the index converges to 0, it provides few opportunities for the index to provide meaningful information to land-use managers. Therefore, we needed to strike a balance between the index converging to the same value as percent native cover or converging to zero (i.e., no room for management action or prioritization).

Although we adopted a structural connectivity approach that is species agnostic, an assumption about dispersal threshold is still needed to be able to calculate connectivity among habitat patches. We chose to adopt a low dispersal distance of 250 m so the indicator would be sensitive to species with dispersal limitations. If landscape connectivity is maintained for species with limited dispersal ability, species with much larger dispersal abilities will also be conserved. To apply the dispersal distance for calculating the Landscape Connectivity indicator, we followed an approach by Blake and Baarda (2018) and assigned the dispersal distance as the maximum distance of direct dispersal for the majority of species (95%) and twice the dispersal distance (500 m) for the remaining 5% of the species. This means that species have a 5% probability of direct dispersal to another patch 250 m away. It is important to acknowledge that rare long distance dispersal events occur. However, a maximum cut-off value is required to make the indicator computation feasible. Therefore, when calculating the Euclidean distance between two habitat patches, patches would have a 0% probability of direct dispersal if they were more than twice the dispersal distance (500 m) apart (Blake and Baarda, 2018). It is important to note that this maximum cut-off value does not limit the ability of species to move large distances within a watershed by moving through multiple native habitat patches that are close together (e.g., as steppingstones).

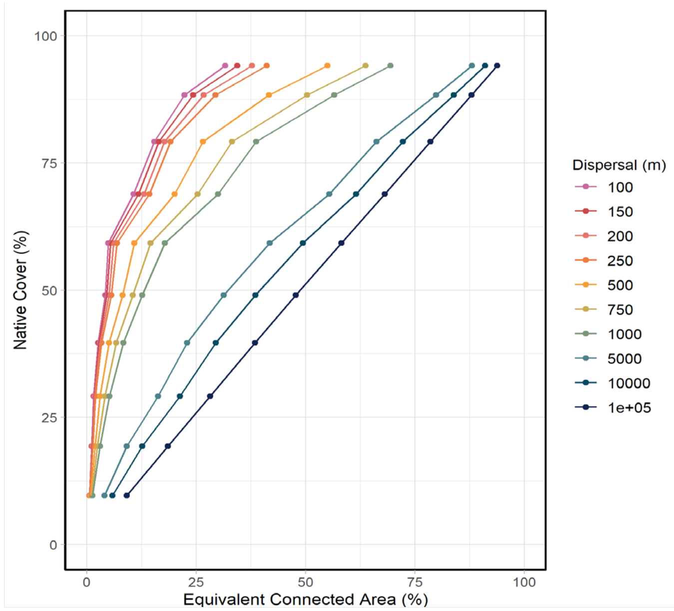

Figure 2. Relationship between the ECA index and percent native cover for multiple dispersal distances (m).

2.4.2 Cost distance

The ECA index has the flexibility to weigh the connections (i.e., links) between viable patches (i.e., nodes) based on the Euclidean distance between edges of patches, and the predicted cost (i.e., resistance) human footprint features or native landcover types exert on species. We drew on two published studies to assign cost values. Marrec et al. (2020) developed a set of cost values for human footprint features based on the 2014 Human Footprint Inventory. The relative values of human modification, ranging between 0–1, were rescaled between 1–10 to allow for these costs to impact connectivity within a watershed, while acknowledging its impact should be secondary to the effects of habitat loss (Table 3). Cost values of 1 indicate there is no additional cost to move between patches on top of the Euclidian distance between them (1 × distance between patches for calculating p_{ij}), while a cost of 10 indicates it is 10 times more difficult to move between patches. To account for the variation in the degree of anthropogenic disturbances between forested (e.g., Green Area) and urbanized and agricultural (White Area) parts of the province (Government of Alberta, 2022), we used the cost values developed for the forested area of the province for Upland Forest and Lowland Forest habitats and the values developed for the agricultural region for Grass-Shrub habitats.

For native habitat types, we used cost values developed by Blake and Baarda (2018) (Table 4). Each habitat type has unique cost values associated with dispersing through unlike habitats (i.e., Grass-Shrub habitats dispersing through Upland Forest habitats had a lower cost than moving through Lowland Forest habitats). For Open Water and Bare Ground habitat types, we chose to use the maximum cost value of 10. This value was chosen because these habitat types are generally unsuitable for the terrestrial species represented by our 250 m dispersal distance (e.g., vascular plants). It is important to note that the majority of Open Water and Bare Ground habitat types remain consistent in both the current and reference landscapes, or transition to footprint types that also have the maximum cost value. Only 0.05% of the landcover in Alberta, about 340 km^2, transitions from the maximum cost value in the reference landscape to a lower cost value under current conditions. Therefore, the assignment of these cost values for Open Water and Bare Ground habitats should have minimal impact on the final indicator value.

It is computationally intensive to determine the least-cost path between all viable habitat patches. This could make it difficult to incorporate this indicator into management practices. Therefore, we calculated cost distances using a 10 m raster and then calculated the average value for each HUC-8 watershed. It has been shown that using an average cost value results in less than a 1% difference in overall connectivity while significantly reducing the computational costs (Saura et al., 2011). The mean cost value for each HUC-8 watershed is calculated using both the backfilled reference condition and the appropriate Human Footprint Inventory (e.g., 2010, 2018, 2019, 2020, or 2021). Appendix 2 shows average cost distances for Grass-Shrub, Upland Forest, and Lowland Forest habitat types under the reference conditions and in 2021, as well as percent changes of average cost distances for the three habitat types between 2021 and reference conditions.

Table 3. Cost values of anthropogenic features for Upland Forest, Lowland Forest, and Grass-Shrub modified from Marrec et al. (2020). Numbers after HARVEST-AREA denote the age of the harvest area (i.e., 0-4, 4-15, and 15+ years).

Feature type Marrec et al. 2020	Feature type ABMI	Upland and Lowland Forest Cost	Grass-Shrub Cost
Disturbed Vegetation	CULTIVATION_ABANDONED	7.75	8.65
Crop	FRUIT-VEGETABLES	7.75	8.65
Gravel/sand/coal mine	GRVL-SAND-PIT	10	10
Gravel/sand/coal mine	MINES-COAL	10	10
Well active	WELL-BIT	4.6	8.2
Well active	WELL-CASED	4.6	8.2
Well active	WELL-OTHER	4.6	8.2
Well active	WELL-UNKNOWN	4.6	8.2
Landfill	RIS-OVERBURDEN-DUMP	10	10
Mine wastes	RIS-WASTE	10	10
Mine wastes	TAILING-PILE	10	10
Clearing (well pad)	WELL-CLEARED-NOT-DRILLED	6.4	5.5
Industrial Facility	CAMP-INDUSTRIAL	10	10
Clearing (well pad)	CLEARING-WELLPAD-UNCONFIRMED	6.4	5.5
Industrial Facility	FACILITY-OTHER	10	10
Industrial Facility	FACILITY-UNKNOWN	10	10
Industrial Facility	MILL	10	10
Industrial Facility	MISC-OIL-GAS-FACILITY	10	10
Industrial Facility	OIL-GAS-PLANT	10	10
Industrial Facility	RIS-CAMP-INDUSTRIAL	10	10
Clearing (unknown)	RIS-CLEARING-UNKNOWN	6.4	5.5
Industrial Facility	RIS-FACILITY-OPERATIONS	10	10
Industrial Facility	RIS-FACILITY-UNKNOWN	10	10
Industrial Facility	RIS-PLANT	10	10
Industrial Facility	RIS-TANK-FARM	10	10
Industrial Facility	URBAN-INDUSTRIAL	10	10
Canal	RIS-DRAINAGE	10	10
Cut block	HARVEST-AREA-15+	1	1
Cut block	HARVEST-AREA-4-15	6.4	6.4
Cut block	HARVEST-AREA-0-4	10	10
Average of Borrow pit dry + Borrow pit wet	BORROWPITS	9.1	9.1
Disturbed Vegetation	RIS-RECLAIMED-CERTIFIED	7.3	7.3
Disturbed Vegetation	RIS-RECLAIMED-PERMANENT	7.3	7.3
Disturbed Vegetation	RIS-RECLAIMED-TEMP	7.3	7.3
Disturbed Vegetation	RIS-RECLAIM-READY	7.3	7.3
Disturbed Vegetation	RIS-SOIL-REPLACED	7.3	7.3
Disturbed Vegetation	RIS-SOIL-SALVAGED	7.3	7.3
Paved Road	AIRP-RUNWAY	10	10
Paved Road	INTERCHANGE-RAMP	10	10
Paved Road	RIS-AIRP-RUNWAY	10	10
Road Paved	ROAD-UNCLASSIFIED	10	10
Winter Access Road	ROAD-WINTER	4.6	4.6
Trail	TRUCK-TRAIL	1.9	2.8
Pre-low-impact seismic line	CONVENTIONAL-SEISMIC	1	6.4
Crop	CROP	7.75	8.65
CFO	CFO	10	10
Rough pasture	ROUGH_PASTURE	3.25	4.15
Tame pasture	TAME_PASTURE	6.4	7.3
Pit lake	MINES-PITLAKE	10	10
Peat	PEAT	8.2	8.2
Well abandoned	WELL-ABAND	1.9	2.8

Oil sand mine	MINES-OILSANDS	10	10
Oil sand mine	OPEN-PIT-MINE	10	10
Mine (RIS)	RIS-MINES-OILSANDS	10	10
Mine (RIS)	RIS-OILSANDS-RMS	10	10
Gas well	WELL-GAS	9.1	8.2
Oil well	WELL-OIL	4.6	8.2
Windmill	WINDMILLS	10	10
Landfill	LANDFILL	10	10
Transfer station	TRANSFER_STATION	10	10
Lagoon	LAGOON	10	10
Tailing pond (RIS)	RIS-TAILING-POND	10	10
Sump	SUMP	10	10
Tailing pond	TAILING-POND	10	10
Clearing (unknown)	CLEARING-UNKNOWN	6.4	5.5
Country residence	COUNTRY-RESIDENCE	5.5	5.5
Clearing (residence)	RESIDENCE_CLEARING	7.75	7.75
Rural residence	RURAL-RESIDENCE	5.5	5.5
Urban residence	URBAN-RESIDENCE	10	10
Campground	CAMPGROUND	5.5	5.5
Golf course	GOLFCOURSE	6.4	6.85
Greenspace	GREENSPACE	3.25	3.25
Recreation	RECREATION	3.25	4.15
Runway	RUNWAY	5.5	5.5
Surrounding vegetation	SURROUNDING-VEG	5.5	5.5
Canal	CANAL	10	10
Reservoir	RESERVOIR	10	10
Borrow pit dry	BORROWPIT-DRY	8.2	8.2
Borrow pit wet	BORROWPIT-WET	10	10
Dugout	DUGOUT	10	10
Borrow pit (RIS)	RIS-BORROWPITS	10	10
Window (RIS)	RIS-WINDROW	10	10
Railway/road verge	VEGETATED-EDGE-RAILWAYS	5.5	5.5
Railway/road verge	VEGETATED-EDGE-ROADS	5.5	5.5
Paved Road	RIS-ROAD	10	10
Abandoned railway	RLWY-ABANDONED	6.4	6.4
Double track railway	RLWY-DBL-TRACK	9.1	9.1
Abandoned railway	RLWY-FORMER	6.4	6.4
Multiple railway and spur	RLWY-MLT-TRACK	9.1	9.1
Single track railway	RLWY-SGL-TRACK	9.1	9.1
Multiple railway and spur	RLWY-SPUR	9.1	9.1
Gravel road	ROAD-GRAVEL-1L	8.2	8.2
Gravel road	ROAD-GRAVEL-2L	8.2	8.2
Paved road	ROAD-PAVED-1L	10	10
Paved road	ROAD-PAVED-2L	10	10
Paved road	ROAD-PAVED-3L	10	10
Paved road	ROAD-PAVED-4L	10	10
Paved road	ROAD-PAVED-5L	10	10
Paved road	ROAD-PAVED-6L	10	10
Paved road	ROAD-PAVED-7L	10	10
Paved road	ROAD-PAVED-DIV	10	10
Paved road	ROAD-PAVED-UNDIV-1L	10	10
Paved road	ROAD-PAVED-UNDIV-2L	10	10
Paved road	ROAD-PAVED-UNDIV-4L	10	10
Unimproved road	ROAD-UNIMPROVED	4.6	5.5
Unpaved road	ROAD-UNPAVED-1L	7.3	7.3
Unpaved road	ROAD-UNPAVED-2L	7.3	7.3
Winter Access Road	ROAD-WINTER-ACCESS	4.6	4.6

Trail	TRAIL	1.9	2.8
Low-impact seismic line	LOW-IMPACT-SEISMIC	1	1.9
Pipeline	PIPELINE	6.85	6.85
Transmission line (RIS)	RIS-TRANSMISSION-LINE	10	10
Transmission line (RIS)	RIS-UTILITIES	10	10
Transmission line	TRANSMISSION-LINE	3.7	6.4

Table 4. Cost values of native habitat types, using the values from Blake and Baarda (2018) for species to move through each other. Maximum values of 10 were used for Open Water and Bare Ground habitats.

Native Habitat	Upland Forest Cost	Lowland Forest Cost	Grass-Shrub Cost
Upland Forest	1	1.75	3.2
Lowland Forest	1.75	1	4.375
Grass-Shrub	2.5	1.75	1
Bare Ground	10	10	10
Open Water	10	10	10

2.4.3 Minimum viable patch size

Every species requires a minimum amount of habitat to support aspects of their ecology (e.g., foraging and breeding). The amount of area required can range from a few square centimeters (e.g., microhabitats, moss on a decaying log), to very large areas that support larger organisms with bigger dispersal capabilities (e.g., large mammals). This range in variation makes it challenging to choose a minimum viable patch size that is meaningful across multiple species.

Using guidance from both the NatureServe Conservation Status Assessment (Master et al., 2012) and landscape disturbance simulations (Figure 3), we chose a minimum viable patch size of one hectare (0.01 km^2). Setting a minimum viable patch size that is relatively small provides several key benefits:

- Allows the indicator to be responsive to new disturbance in small (but greater than one hectare) native habitat patches compared to a larger minimum viable patch size,
- Prevents the indicator from converging rapidly to zero under varying amounts of human disturbance (Figure 3) compared to a larger minimum viable patch size, and
- Reduces the computational resources required for this indicator as we ensure that polygon slivers are not considered as habitat patches compared to not having a minimum viable patch size.

We acknowledge that this minimum viable patch size does not represent all species. However, from the perspective of land-use planning, using a single minimum viable patch size allows for robust comparisons across regions.

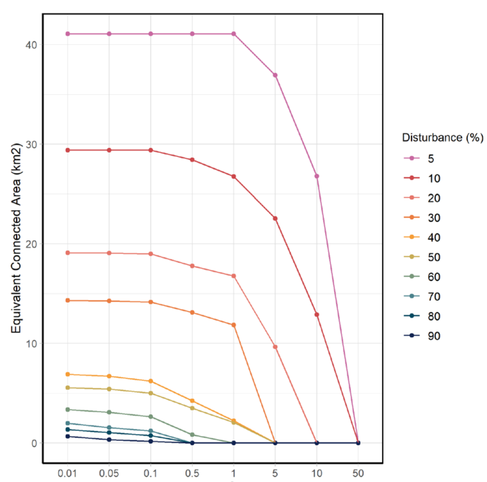

Figure 3. Response of the ECA index as we increase the minimum viable patch size under multiple levels of landscape disturbance.

2.4.4 Reference condition

We calculated the ECA index for multiple time steps (2010, 2018, 2019, 2020 and 2021) compared to a reference condition. The reference condition represents the state of the landscape in the absence of human footprint (i.e., backfilled layer), not a pre-colonialization landscape condition. In short, this is derived by filling in human footprint based on neighbouring native vegetation (Alberta Biodiversity Monitoring Institute, 2017).

The backfilled condition allows us to isolate the impacts of anthropogenic disturbance from other natural changes to landcover types over time.

2.4.5 Recovery of forest harvest areas

Applying recovery to forest harvest areas gives a more realistic representation of how harvest areas interact with the surrounding ecosystem. It is well known in the scientific literature that forest harvesting, particularly clearcut harvesting, differs from wildfire in their impacts on biodiversity (McRae et al., 2001). Although harvest areas provide habitat for some species, they are not equivalent to post-fire forest stands of the same age. At the same time, forest harvest areas do recover; therefore, recovery curves recommended by Huggard and Kremsater (2015) for deciduous and coniferous forest types were applied when calculating landscape connectivity for the three habitat types (Figure 4).

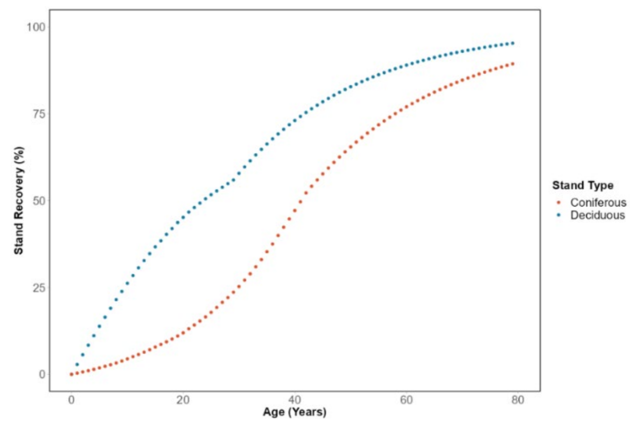

Figure 4. Forest recovery curves as described by Huggard and Kremsater (2015).

For harvest areas, recovery is accounted for in a continuous fashion, with recovery varying from 0% to 100% depending on forest age and the distribution of harvested coniferous and deciduous stands. Harvest areas 80 years or older are considered fully recovered (Huggard and Kremsater, 2015).

Forest harvest areas are the only type of footprint that is allowed to recover in the calculation of indicator conditions. As we currently do not have sufficient data to distinguish partially harvested areas from clearcut areas, all forest harvest areas are treated as if they are a clearcut.

There is currently insufficient research to allow for recovery of other footprint types. For example, Bayne et al. (2011) demonstrated that although seismic line age can be used to predict vegetation recovery on seismic lines, such models were not very accurate. Other alternatives were proposed, but as pointed out by Bayne et al. (2011), no one value is “right” for defining a seismic line as recovered. In addition, most seismic lines have limited recovery, even after 35 (Lee and Boutin, 2006) and 50 (van Rensen et al., 2015) years. Recovery in other footprint types (e.g., seismic lines, wellpads) will be deferred until sufficient supporting information becomes available.

3. Results

3.1 Aggregated landscape connectivity

Landscape connectivity was high in northeastern Alberta and the Rocky Mountains for all five years, as illustrated by higher indicator values in 2010 and 2021 (Figure 5). On the other hand, lower connectivity values were detected in more developed areas such as the southern part of the province. Across all HUC-8 watersheds, landscape connectivity values ranged from 1.2% to 100% for all five years, with provincial averages of 35.5%, 33.7%, 33.5%, 33.4%, and 33.3% respectively, for 2010, 2018, 2019, 2020, and 2021. Results for all five years are available on GeoDiscover Alberta (Landscape Connectivity Indicator for Alberta).

Landscape connectivity declined from 2010 to 2021 for most watersheds, with an average decline of 2.24% (sd = 3.16%) across all watersheds in the province (Figure 5). Of the 422 HUC-8 watersheds, landscape connectivity increased in 24 watersheds, decreased in 394 watersheds, and was stable in 4 watersheds. For the 24 watersheds that observed increases, only 7 had increases greater than 0.5%, while the remaining 17 had increases smaller than 0.5%. Of the 394 watersheds experiencing declines, 152 experienced declines greater than 2%, and 50 experienced declines greater than 5% (Figure 5). For two watersheds (HUC 18040203 and HUC 19010305), indicator conditions declined more than 25% (25.5% for HUC 18040203 and 25.9% for HUC 19010305) over the 11-year period, from 64.1% to 38.6% for HUC 18040203 and from 70.6% to 44.7% for HUC 19010305.

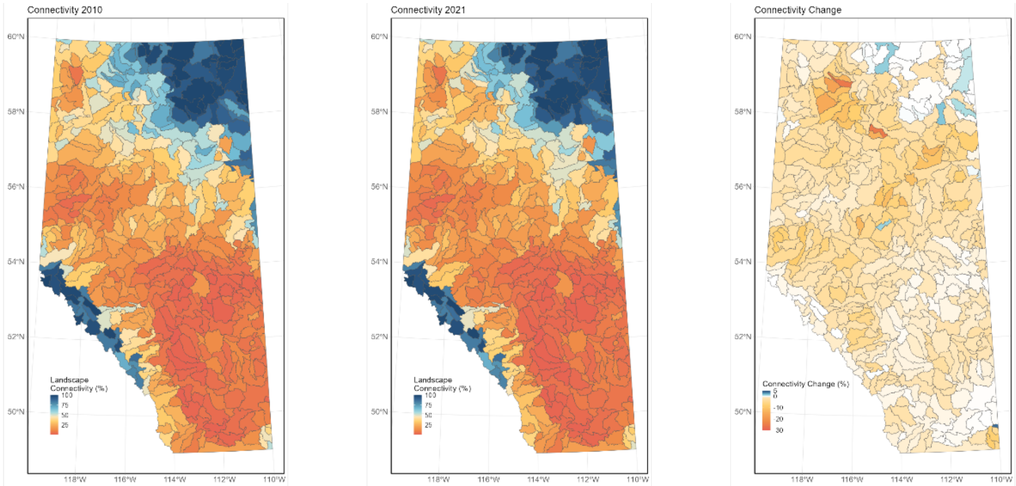

Figure 5. Status of landscape connectivity in 2010 (left), 2021 (centre), and the connectivity change (right) during this period.

3.2 Landscape connectivity for Grass-Shrub

Landscape connectivity for Grass-Shrub habitat type was low throughout the Grassland and Parkland Natural Regions (Figure 6). Focusing on watersheds where Grass-Shrub were the dominant habitat type under the reference condition (66 watersheds), average connectivity was 8.25% in 2010 (sd = 10.2%) and declined to 7.1% (sd = 8.9%) in 2021. Even though some watersheds saw large declines in connectivity, these are often restricted to areas where Grass-Shrub habitats are rare. However, Grass-Shrub habitats are the least connected habitat type in the province.

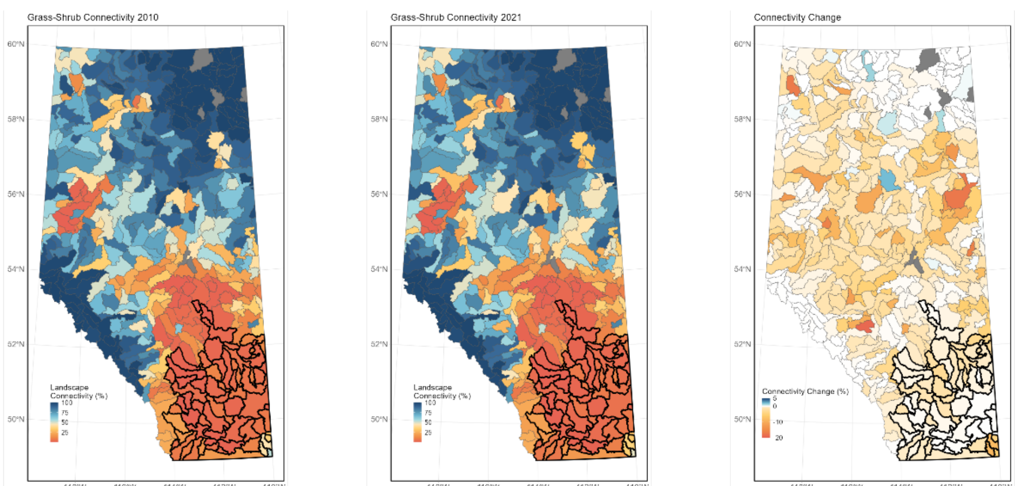

Figure 6. Status of landscape connectivity for Grass-Shrub habitat type in 2010 (left), 2021 (centre), and the percent change (right) during this period. Watersheds outlined in black represent the watersheds where Grass-Shrub is the dominant habitat type. Watersheds where Grass-Shrub habitat type was not observed under the reference condition are colored in grey.

3.3 Landscape connectivity for Upland Forest

Landscape connectivity for Upland Forest habitat type was low throughout the Parkland and sections of the Boreal Forest Natural Regions (Figure 7). Focusing on watersheds where Upland Forest was the dominant habitat type (259 watersheds), average connectivity was 30.8% in 2010 (sd = 32.4%) and declined to 28.9% (sd = 32.7%) in 2021.

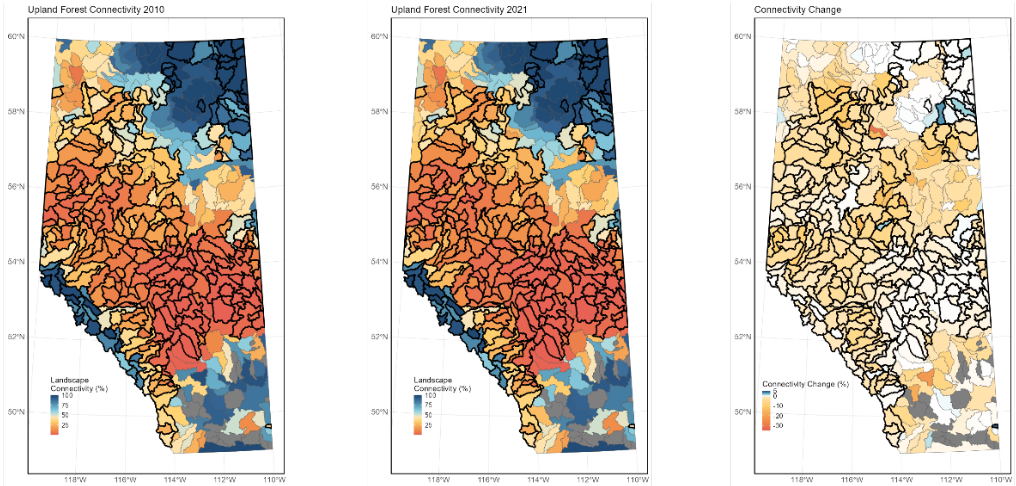

Figure 7. Status of landscape connectivity for Upland Forest habitat type in 2010 (left), 2021 (centre), and the percent change (right) during this period. Watersheds outlined in black represent the watersheds where Upland Forest is the dominant habitat type. Watersheds where Upland Forest habitat type was not observed under the reference condition are colored in grey.

3.4 Landscape connectivity for Lowland Forest

Landscape connectivity for Lowland Forest habitat type was low throughout several Natural Regions, but had pockets of relatively connected habitat (Figure 8). Focusing on watersheds where Lowland Forest was the dominant habitat type (97 watersheds), average connectivity was 53.2% in 2010 (sd = 25.2%) and declined to 49.8% (sd = 25.5%) in 2021 (Figure 8). This is the most connected habitat type in the province. However, it also had the largest average decline (3.4%) in connectivity between 2010 and 2021.

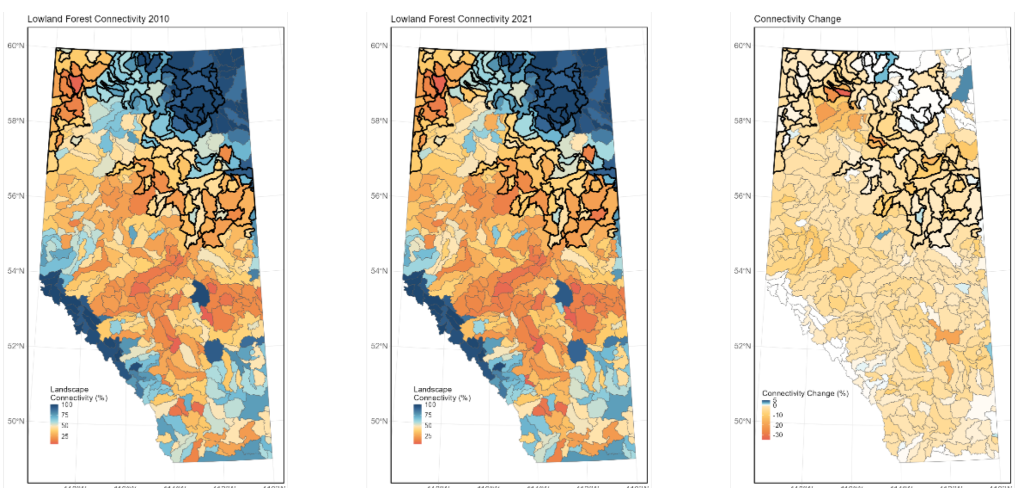

Figure 8. Status of landscape connectivity for Lowland Forest habitat type in 2010 (left), 2021 (centre), and the percent change (right) during this period. Watersheds outlined in black represent the watersheds where Lowland Forest is the dominant habitat type.

3.5 Interpretation

There are two main factors that can result in lower landscape connectivity. The first factor is the direct loss of habitat. As we are comparing current landscape connectivity to those under a reference condition, any direct loss of habitat results in a lower connectivity. This is true even if the remaining habitat under current conditions is clumped together (i.e., highly connected within the remaining fragments of habitat).

The second factor is the fragmentation of habitat patches. There are disturbances, such as linear features, that are more likely to fragment habitat patches. Even though these features have a small direct effect on habitat removal, they can increase the number of habitat patches in a region. This means species are no longer able to disperse through a singular large habitat patch, but instead must cross multiple human footprint features to reach the same location. Even if a species has a high probability of successfully dispersing across a single footprint feature (e.g., 90%), the cumulative impact of having to cross multiple features (e.g., 10 features) results in a low probability of success ($0.9^{10} \times 100\% = 34.9\%$). This cumulative impact of fragmenting footprint features can create situations where landscape connectivity is low despite having large amounts of native habitat. These situations show how the Landscape Connectivity indicator provides novel information about the impacts of footprint outside of the direct loss of habitat.

4. Limitations

All indicators, as representations of a component of the environment, have limitations. A single indicator cannot measure all aspects of habitat quantity and/or quality. The Landscape Connectivity indicator is intended to serve as a general indicator of habitat connectivity at the regional and sub-regional levels. As such, we acknowledge and accept limitations associated with the indicator:

- This indicator does not capture the connectivity of migratory species or identify specific connectivity corridors. The ECA index was calculated within HUC-8 watersheds.
- Species range in their abilities to disperse and colonize habitats. While this indicator is intended to represent landscape connectivity for a large suite of species, it will not capture all species.
- Recovery of human footprint is only incorporated for forest harvest areas through recovery curves and for those features that have been reclaimed and are no longer present in the Human Footprint Inventory.

5. Supporting GIS Information

The Landscape Connectivity indicator data layer is available on GeoDiscover Alberta (Landscape Connectivity Indicator for Alberta). The layer presents aggregated landscape connectivity values and landscape connectivity for Upland Forest, Lowland Forest and Grass-Shrub for HUC-8 watersheds in Alberta over a time series (2010, 2018, 2019, 2020, 2021). Table 5 describes the attributes associated with the published data layer. Note that if a particular habitat type is not present in a HUC-8 watershed, the connectivity value is coded as -9999 for all time steps.

Table 5. Attributes associated with the Landscape Connectivity indicator data layer.

Attribute	Definition
HUC_2	HUC 2 watershed ID
HUC_4	HUC 4 watershed ID
HUC_6	HUC 6 watershed ID
HUC_8	HUC 8 watershed ID
LC2010 LC2018 LC2019 LC2020 LC2021	Aggregated landscape connectivity of each HUC 8 watershed in 2010, 2018, 2019, 2020, and 2021
Upland2010 Upland2018 Upland2019 Upland2020 Upland2021	Landscape connectivity of each HUC 8 watershed for Upland Forest in 2010, 2018, 2019, 2020, and 2021
Low2010 Low2018 Low2019 Low2020 Low2021	Landscape connectivity of each HUC 8 watershed for Lowland Forest in 2010, 2018, 2019, 2020, and 2021
Grass2010 Grass2018 Grass2019 Grass2020 Grass2021	Landscape connectivity of each HUC 8 watershed for Grass-Shrub in 2010, 2018, 2019, 2020, and 2021

For any questions regarding the information presented in this document, or about other applications of this indicator, please contact Lands Planning Branch, Alberta Environment and Protected Areas (EPA.Planning@gov.ab.ca) or refer to the following repository: https://abbiodiversity.github.io/LandscapeConnectivity/.

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Appendix 1: Review of Landscape Connectivity Approaches

Review of Landscape Connectivity Approaches

FINAL REPORT

Prepared for:
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Alberta Biodiversity Monitoring Institute

July 2019

Project 1901

FIERA
Biological Consulting

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1.0 Introduction

1.1. Background

As part of environmental management in Alberta, a biodiversity management framework (BMF) is being developed for each of the seven Land-use Framework (LuF) planning regions. The BMF supports the vision and goals of the LuF by including biodiversity objectives within regional plans, as well as providing context for the management of the effects of development on the environment. Importantly, the BMF defines the biological indicators that are used to monitor and respond to cumulative effects; thus, an integral part of developing each BMF is to identify relevant, meaningful, and practical indicators for assessing and monitoring biodiversity outcomes. Indicators in the BMF are arranged into tiers, with the top tier (Tier 1) acting as a composite indicator of biodiversity that is consistent across all regions, and the lower tiers (Tiers 2 and 3) providing regionally significant information to complement the assessment of biodiversity. Tier 2 indicators play a key role in the BMF by directly addressing biodiversity issues and reflecting species and habitats of special interest in each region. These indicators are also associated with thresholds that define the risk and tolerance for change based on current and reference conditions.

Currently, Tier 2 indicators are being developed for the South Saskatchewan Region, and landscape connectivity has been identified as an important supporting component of the Tier 1 biodiversity indicator that describes the amount of native or natural cover. Landscape connectivity directly and indirectly affects biodiversity, species richness, species persistence, ecosystem function, and the provision of ecosystem services, and is thus an ideal regional indicator. The approach used to quantify connectivity, however, can vary depending upon the purpose, application, theoretical foundation, assumptions, and data requirements; therefore, candidate indicators must be thoughtfully and thoroughly evaluated to ensure that the most appropriate indicator(s) is/are being selected. Further, each regional plan reflects different values, priorities, land uses, and ecosystems, and thus, potential connectivity indicators should be adaptable, translatable, and reflective of the conditions within each region, such that connectivity can be meaningfully assessed and monitored.

1.2. Report Objectives

The overall goal of this report is to support the selection and development of a connectivity indicator for inclusion in regional BMFs by providing a summary of the scientific approaches for analyzing and assessing landscape connectivity. This report compiles and reviews a suite of potential approaches that have been previously applied in scientific studies and/or land use planning exercises, and further assesses the suitability of each approach to meet regional planning needs and serve as a Tier 2 BMF indicator. Importantly, this information review and initial critique provides the necessary background that the BMF Science Technical Committee (STC) can use to support the process of selecting the most suitable option for assessing connectivity as part of regional BMFs. In support of this overall project goal, this report includes the following:

1) An overview of the scientific concept and theory of landscape connectivity, including the most common definitions, general approaches, methodological considerations, and practical issues for measuring and assessing connectivity;
2) A detailed overview and review of the four potential methodological approaches and their associated measures or metrics that are commonly used to assess connectivity;
3) A critical assessment and evaluation of each connectivity assessment approach, including a critique of whether the approach is a reliable indicator of connectivity based upon a comprehensive list of evaluation criteria.

2.0 Connectivity Overview

2.1. Why is Landscape Connectivity Important?

The concept of landscape connectivity was introduced over 30 years ago (Merriam 1984), and since then, the term connectivity has become embedded into both research and political agendas, which reflects how approachable and appealing the idea of connectivity is across many different perspectives and stakeholders. Defined as the degree to which landscapes allow species to move freely and ecological processes to function unimpeded (UNEP 2019), it is generally accepted that connected habitats are more effective in preserving species and ecological functions. Greater connectivity promotes movement and dispersal between populations, and is therefore crucial to maintaining regional populations, gene flow, and overall landscape biodiversity and ecosystem health over time (Fahrig and Merriam 1985; Lefkovitch and Fahrig 1985; Hanski 1994; Hanski 1999; Baguette et al. 2013). Thus, connectivity provides a desirable management objective that is conceptually easy to understand and communicate; however, practically speaking, measuring and assessing connectivity can be a difficult and overwhelming endeavour because it requires a clear definition of the type, purpose, landscape, goals, and users of the connectivity analysis. The most critical step in a connectivity analysis is clearly articulating the question and goals of the assessment.

A connectivity assessment can be associated with many types of goals or objectives, ranging from specific and fine scale to more general and broad-scale, each of which necessitates different types of analyses and information outputs. Some common reasons for undertaking a connectivity analysis include:

- Assessing habitat connectivity for a particular species, population, or network of core areas;
- Identifying patches or areas within a particular geography that contribute most to connectivity;
- Identifying areas where connectivity is lacking or can be improved;
- Increasing connections or corridors between existing features;
- Planning landscape connectivity to accommodate climate change and species range shifts.

Each of these objectives require different decisions to be made, analytical approaches, and types and amounts of data, and accordingly, approaches have been developed to complement the different types of connectivity questions that are commonly being asked by land managers and policy makers.

2.2. Scientific Approaches to Connectivity Analysis

With the interest in and range of objectives related to assessing connectivity, it is no surprise that a large number of approaches and analytical tools have been developed to model and analyze connectivity. Each of these approaches and tools have been built based on the type of connectivity being analyzed, and the corresponding theoretical frameworks and assumptions about the landscape and the species moving through it, and thus, no one approach or tool is best suited to all connectivity analyses and questions.

Despite the different definitions and approaches, an assumption that is common to all is that there is a spatial relationship among the patches of interest, and that the landscape intervening those patches will influence that relationship (Singleton and McRae 2013). Thus, the dominant approaches to analyzing connectivity are spatially explicit and consider movement to some extent. Despite these two common components, various approaches to measuring connectivity have different theoretical frameworks and associated assumptions, which means there are several key decision points that must be recognized and understood when determining which approach is best suited to the study and questions of interest. These include defining for who or what connectivity is being modelled, and how to determine and measure the existence and strength of the connections.

2.2.1. Connectivity for Who or What?

The first step is deciding on whether to assess the connectivity of species or landscape elements (e.g., natural areas, parks, etc.), and this will be intimately tied to the objective or goal of the connectivity analysis. Assessing connectivity for species requires the selection of one or more focal species and a strong understanding of each selected species' habitat, behaviour, and movement and dispersal behaviour (Brodie et al. 2015). A species-based approach is best suited to answering questions concerning connectivity of species of interest, or for addressing particular questions about the impact of development scenarios on species movement or dispersal. On the other hand, a landscape elements-based approach tends to be more applicable when a more general idea of ecological connectivity is desired, or when the question or goal of the connectivity analysis is to determine the effectiveness of an existing network of features, such as protected areas, parks, and/or intact natural areas. The landscape elements approach is often applied in regional or broad-scale assessments, because species data may be lacking for the entire region, and/or the interest is in generally understanding connectivity for managed units of land and understanding where there may be gaps in connectivity at the landscape scale. In some very large, multi-year projects, these two approaches are integrated to determine the degree of overlap between the coverage of existing natural or protected areas and the areas important for species connectivity (e.g., Spencer et al. 2010; WHCWG 2010).

Whether species or landscape elements are being studied, the majority of connectivity analyses assess or model connections between patches or core areas of landscape. Thus, another challenge to a connectivity analysis is defining, identifying, and delineating these core patches (Rudnick et al. 2012). When a focal species approach is employed, core areas are based on areas of suitable habitat for the species or species guild in question, and areas of suitable habitat are determined from species-habitat models and other sources of empirical or biological information (e.g., Haddad 2015; Abrahms et al. 2016). In some cases, an umbrella species approach is applied, in which the habitat use and core areas for a representative large carnivore is assumed to cover those areas needed by smaller species. In other cases, core area maps are developed for a suite of focal species that have been determined to be important in the study area, and then these core area maps are either overlaid to create composite core habitat areas, or the connectivity for each focal species is analyzed individually and the results are then compiled or composited. Alternatively, when landscape elements are being analyzed, core areas are typically pre-defined locations, such as protected areas, or are assigned by determining areas where the landscape has not been impacted by human activity and has a high degree of naturalness or integrity (i.e., no or very low human footprint).

To avoid the decisions and problems associated with identifying core areas, some analyses have begun to apply an approach that does not identify core habitat patches *a priori*, and instead models the entire study area as a connectivity surface with no particular start and end points. One way this is achieved is to buffer the perimeter of the study area and place nodes (start and end points) all along the buffered perimeter to generate predictions of potential connectivity across the entire area (e.g., Koen et al. 2014; Pelletier et al. 2014). Another approach involves designating nodes at every location (i.e., each raster cell) or a large subset of locations designated as locations of low resistance within the study area, modelling dispersal away from each node in all directions using a dispersal kernel, and then summing all of the overlapping kernels to create a continuous surface. Because predictions from this type of approaches are not tied to specific start and end points, results tend to provide a broad or more encompassing picture of landscape connectivity. The downside to this approach is it requires many broad assumptions regarding how species interact with and move through the landscape.

2.2.2. Determining Whether It's Connected

When assessing the connectivity of the landscape or of a network, methods and their associated measures can be considered as either structural, in which the arrangement and physical relationships of landscape elements (e.g., amount of habitat, presence of corridors) are used to measure connectivity, or functional, in which species behaviour, mobility, and interactions with and responses to landscape elements are considered when measuring connectivity (Calabrese and Fagan 2004; Taylor et al. 2006). Both types of approaches range in complexity, with more complex analysis providing more information but requiring more decisions and assumptions, and simpler approaches requiring fewer decisions and assumptions but provide less specific information (Singleton and McRae 2013).

Structural connectivity approaches

Structural measures of connectivity were the initial metrics developed by ecologists and have a longer history of use than functional measures (Taylor et al. 2006; Wiens 2006). Structural connectivity measures are based on the physical characteristics of the landscape, and they are relatively quick and easy to calculate and visualize since they require only a relevant layer of land cover or land use. Metrics attempt to quantify the effect of spatial pattern and arrangement on species' movement, and in doing so may simply describe the physical traits of the landscape and its elements by calculating the number, size, extent, and shape of patches (Fagan and Calabrese 2006), or by calculating patch area and proximity (i.e., distance) in different ways, such as via calculations of the distance among neighbours or patch interspersion.

In general, structural approaches assume that stronger physical relationships and ties between the landscape elements of interest equates to greater connectivity (Kadoya 2009). The use of structural measures is attractive because this method is fast and practical for characterizing connectivity across large areas; however, assuming that only landscape structure determines species movement ignores species' behavioural interactions within the landscape. A major limiting assumption of structural measures is that the matrix, which is the intervening habitat between patches, is homogeneous and benign (Fahrig 2007). In most landscapes, the matrix is heterogeneous and is comprised of a number of cover types in which barriers or impediments may exist that impact and influence species' movements. In many cases, structural metrics have not been tested for how well they actually predict movement (Kadoya 2009), or have only weakly been correlated with dispersal success, and findings have at best been inconsistent in both empirical tests and theoretical simulations (Tischendorf 2001; Bender and Fahrig 2005; Winfree et al. 2005; Baguette and Van Dyck 2007). Therefore, structural connectivity approaches should be reserved for analyzing highly fragmented landscapes where suitable patches are small, isolated, and in which distance is the most important determinant of connectivity (Hanski 1999, Kadoya 2009), and for species for which dispersal success is dependent on physical connections (e.g., corridors) or close proximity between patches (Fagan and Calabrese 2006; Wiens 2006).

Functional connectivity approaches

Because ecologists agree that connectivity depends not just on landscape structure, but also on the movement behaviour of the organism (Tischendorf and Fahrig 2000), focus has shifted away from structural approaches towards the development and use of functional connectivity approaches (Taylor et al. 2006). This has not proven easy (Kadoya 2009); for a method to truly characterize or measure functional connectivity, it must incorporate the spatial arrangement and composition of the landscape, as well as how a particular individual interacts and reacts to elements of the landscape as it is moving between patches (Tischendorf and Fahrig 2000). In heterogeneous landscapes habitat patches may be structurally near to one another, but the presence of barriers or land cover types that are difficult or dangerous to move through make patches functionally difficult to move between. Thus, functional approaches consider and measure connectivity across the entire landscape as viewed from the individual's perspective instead of as a property of a specific patch (Kadoya 2009), and aim to incorporate how the landscape between patches (i.e., the matrix) influences behaviour and movement rates (Baum et al. 2004; Haynes and Cronin 2006).

In order to achieve this, most functional connectivity approaches have relied upon adapting the measurement of distance between locations to reflect the amount of effort or level of ease or difficulty to move across the landscape. Here, a raster is used to model the landscape and each cell reflects how permeable it is to movement, or how easy or hard it is to move through that cell. In these resistance surfaces, the landscape is represented as a cost surface, in which a high cost is considered highly resistant to movement, and the distance to travel between locations is hindered by the cost to travel through obstacles (Marrotte and Bowman 2017). Resistance surfaces can be based on continuous or discrete (categorical) data, and may use actual or transformed values from another modelled layer (e.g., resource selection function, habitat selection layer), or use expert-based assigned values for the raster cells. Notably, the predictions from any connectivity analysis that is resistance surface-based are extremely sensitive to the assigned cell values, so resistance values should be selected so that they appropriately consider the landscape being studied, animal behaviour, physical traits, and the type of movement occurring (e.g., dispersal versus within-home range foraging) (Singleton and McRae 2013).

While arguably more realistic, functional approaches require substantially more data and in-depth knowledge of the characteristics of animal movement for a given landscape, as well as data on the spatial arrangement and composition of the different types of land cover for a given landscape.

2.2.3. Connectivity Across Scales

There is a strong consensus that to fully understand landscape connectivity, analyses should occur at multiple scales (Maciejewski and Cumming 2016), and a multi-scale approach has been applied in several statewide projects in the United States (e.g., Spencer et al. 2010; WHCWG 2010). Broad-scale or regional-scale studies can provide an overview or general picture of connectivity, and finer-scale studies should be used to both add resolution and incorporate local objectives and planning capabilities (Minor and Lookingbill 2010; Singleton and McRae 2013). Importantly, each scale may allow or inhibit certain data sources and types of analysis or assessment, and the study designs for different scales should aim to complement or fill in the information that cannot be provided by the other(s). For example, at a provincial scale, it may be more efficient and realistic to use an approach that is based on data at a coarse scale and accounts for species habitat use and behaviour in a general way, while a regional- or local-scale study might look to basing analyses on focal species and higher resolution data to understand the more nuanced patterns of connectivity that are missed at the provincial scale.

2.3. What is the Purpose of the Connectivity Analysis?

Approaches to analyzing connectivity are often classified primarily as structural or functional, but an alternative and more practical consideration is directly related to the objective of the analysis. This is particularly true when the output of an assessment is to be used to inform planning or management, or to support decision-making as it relates to establishing a benchmark against which comparisons can be made and trends be monitored through time. When considered this way, approaches to connectivity can be classified as being more prioritization and planning focused, versus being more quantification and assessment focused.

Prioritization and planning focused approaches tend to include analyses that produce predictive maps of connectivity that display movement probabilities and identify locations where connectivity is predicted to be low versus high. Maps of predicted connectivity are common to several analytical approaches, including least-cost style models and circuit theory modelling. The predictions from all of these approaches can allow for comparisons of connectivity in a relative way, but predictions are also dependent on the placement of patches or nodes, the parameterization of the resistance layer (i.e., resistance values chosen), and the resolution or scale of the analysis. Further, while the approaches are somewhat complementary, they typically predict different patterns of connectivity spatially, and each approach is more or less suited to different species and different scenarios (Avon and Bèrges 2016). More and more studies are generating predictions from each approach, and then comparing and even combining outputs to analyze and understand landscape connectivity (e.g., Lechner et al. 2015; Proctor et al. 2015; Mallory and Boyce 2019).

Importantly, predictive maps, especially those developed for broad-scale projects, should be considered as decision-support tools and concise expressions of potential or desired future connectivity (Beier et al. 2011). Maps can act as important visual tools, as they make it easy to identify locations where connectivity is important, where it is sensitive and in need of conservation or protection, or where it is lacking and need of improvement. Because of this, connectivity maps can be important tools for expressing a vision and inspiring stakeholders to achieve management goals. Importantly, however, Beier et al. (2011) emphasize that broad-scale maps are not meant to be implementable conservation plans or linkage designs, but rather are meant to depict areas where linkage designs can be developed, or inform where development may negatively impact connectivity. Indeed, connectivity maps are predictions, and accordingly, Wade et al. (2015) suggest that predicted connectivity maps are better thought of as asking the question “if an organism were to travel from A to B, what path(s) could it take?” rather than “how likely is an organism to travel between A and B?”.

In contrast to prioritization and planning focused approaches, quantification and assessment focused approaches use metrics to provide numerical measures of connectivity for the area of interest. Metrics for this purpose are developed by taking measurable components of the landscape (e.g., area, distance) and relating them to ecological theory and hypotheses about connectivity. This defines a mathematical formula for the metric, and the calculated value is a measure of connectivity. In this way, values from the metrics can be used to define baseline conditions and assess change over time, test scenarios of changes in land use land management, or compare connectivity between different areas.

Depending on the objective, an assessment-focussed approach may apply structural metrics, functional metrics, or some combination of the two. For example, structural connectivity metrics may be used to quantify connectivity by simply counting features (e.g., number of corridors) or by calculating an average value across the study area (e.g., mean patch size). These simple metrics are easy to calculate and are applied widely to provide a general assessment of connectivity; however, structural metrics tend to be somewhat unreliable indicators of actual connectivity since the relationship between the calculated value from the metric and what it is saying about connectivity can be counter-intuitive – for example, a greater number of corridors could mean connectivity is high, or that the landscape is fragmented into many small patches (Saura and Pascual-Hortal 2007). When possible, assessments try to apply functional connectivity metrics to quantify connectivity. These more refined metrics incorporate variables describing dispersal probabilities or other species' movement and behaviour information alongside structural landscape variables, and the resulting calculated metric values are used to characterize the landscape connectivity of the area of interest. The most established functional connectivity metrics (e.g., probability of connectivity index) have been developed and tested to address the problems associated with simpler metrics and to ensure that they have properties that allow them to be applied to conservation planning and change analysis applications (Saura and Pascual-Hortal 2007). Importantly, whether structural or functional, metrics are available to measure connectivity in different ways and at different scales (e.g., patch-level versus landscape level). Thus, it is typical practice to select and calculate a set of metrics, which are then compared to ensure the interpretations of the metric values are meaningful and that the assessment of connectivity is reliable (e.g., Albert et al. 2017; McIntyre et al. 2018).

2.4. Assessing Change in Connectivity Over Time

A primary objective of a connectivity assessment may be to provide a baseline or reference to which future assessments can be compared or the impacts of potential future scenarios can be tested. The definition of the baseline or reference condition is dependent upon defining the time or era of the reference, and is also tied directly to the purpose of the connectivity analysis. For example, defining a historic reference for landscape elements generally would involve removing human disturbances and impacts to reflect a past, undisturbed landscape, while a more species-based reference would involve attempting to model habitat selection and use within a past, undisturbed landscape. The model and/or assessment of connectivity for this reference would then reflect the potential ideal or natural connectivity of the landscape, and current and future connectivity could be compared to this past ideal.

Unfortunately, there is no consensus as to which approach or metrics are the most useful for comparison over time, and empirical studies assessing change in connectivity over time are rare (McIntyre et al. 2018). However, it is important to note that assessing change over time reliably and meaningfully requires that an approach be chosen that provides outputs that are standardized and comparable; that is, quantified values or predictions from the connectivity approach being used should have a consistent meaning (i.e., have a standardized value) and should have a rigorous definition and relationship with actual connectivity to avoid errors in interpretation. A consideration of the relevant spatial scale for change in the study area should also be considered, since as the study area increases in size, relatively smaller changes in land use and connectivity will become less and less apparent (i.e., for very large areas, the percent change over time can be expected to be quite small).

3.0 Overview of Potential Approaches

As part of the larger biodiversity objectives stated in the South Saskatchewan Region BMF, terrestrial habitat connectivity has been identified as a Tier 2 indicator. The goal of a Tier 2 indicator is to provide regionally significant information to complement the assessment of biodiversity, and Tier 2 indicators should directly address biodiversity issues and reflect species and habitats of special interest in each region. Thus, a connectivity indicator should come from an approach that is able to incorporate regional information, and should also produce or be able to be adapted to provide a measure that can be used to assess and measure change in landscape connectivity over time. Because connectivity may also be identified as a Tier 2 indicator in other planning regions, the indicator should also allow for comparisons across regions.

With this in mind, there are several approaches that have been developed to quantify landscape connectivity; however, each of these approaches does so in a different way and for different purposes. This section presents an overview of four potential approaches that could be used to develop an indicator of landscape connectivity to support regional planning in Alberta. These approaches were selected because they are the most prominent and widely applied techniques for predicting or assessing connectivity. Other approaches, such as spatially explicit population models (SEPMs) (Conroy et al. 1995; Dunning et al. 1995; Moilanen and Hanski 2001) and individual-based models (Tracey 2016; Pe’er et al. 2011; Allen et al. 2016; Landguth et al. 2017) were not considered here because these methods rely heavily on species-specific biological information and/or global positioning system (GPS) movement data and are computationally demanding; thus, these approaches are not realistic candidates for use as a regional indicator.

The general explanations and reviews provided in this section set the stage for a more detailed critique of the appropriateness of each approach to provide a suitable regional indicator, which is provided in Section 4. Two of the approaches presented in this section, effective mesh size and circuit theory connectivity modelling, have previously or are currently being explored for use as an indicator in the BMFs. The two other approaches considered in this section, least-cost modelling and graph theory, have been included because they are very common approaches for assessing landscape connectivity.

3.1. Effective Mesh Size

3.1.1. Overview

Effective mesh size is a landscape patch or pattern metric. Landscape patch metrics are simple summaries of the composition and configuration of elements in the landscape and are used to assess structural connectivity. While this type of metric is useful for measuring landscape structure, it does not measure ecological function directly; rather, patch metrics assess the degree of landscape fragmentation, which is a measure of the breaking up or dissection of the natural landscape into smaller pieces. Using fragmentation to assess connectivity assumes that the division of the landscape affects a species' ability to move through the landscape, which may hold true for some species, but not for others (Calabrese and Fagan 2004). This style of metric is generally summarized across a landscape unit (e.g., an ecoregion, a watershed, a municipality, a hexagon) and is less spatially explicit than other approaches; however, this also means that the calculation is less data and computationally intensive.

Effective mesh size is a metric that was proposed by Jaeger (2000) to measure landscape fragmentation and was developed to more consistently and meaningfully quantify fragmentation across all phases (i.e., types) of fragmentation. Effective mesh size is the average size (area) of an unfragmented area in the study area, and ranges from zero (completely fragmented) to the size of the landscape being studied (no fragmentation). It can thought of as an expression of the probability that any two locations in the landscape are not separated by barriers, or also interpreted as the average size of the area in a given landscape can be accessed without crossing barriers (Girvetz et al. 2008).

3.1.2. Method

The calculation of effective mesh size is based solely on the areas of all natural habitat patches; these natural areas are defined by first determining the barriers or fragmentation geometries that are dissecting the habitat patches. Thus, defining what features are fragmenting the landscape is the most important decision when calculating effective mesh size. Because it is measuring only the structural component of connectivity, fragmentation geometries are considered complete barriers, and therefore, should be chosen to reflect the potential for individuals to cross them. In other words, the calculation of effective mesh size is completely sensitive to the definition of the fragmentation geometries. For example, if fragmentation geometries are chosen very liberally and include features that animals may actually cross, such as cutlines or agricultural fields, structural connectivity as measured by effective mesh size will be underestimated. Conversely, if fragmentation geometries are defined very conservatively, effective mesh size may overestimate structural connectivity. Thus, it is common practice to define fragmentation geometries in several different ways (e.g., just major roads, all roads, all linear features), and calculate the metric for each fragmentation geometry.

Modifications to the effective mesh size approach have been made to reduce the sensitivity of the analysis to artificial boundaries (i.e., the cross-boundary connections, or CBC procedure, by Moser et al. 2007) and to allow for differential weighting of barrier strength for different fragmentation geometries and relative position of patches (Jaeger 2007). The cross-boundary connections procedure is the method that has been typically applied within recent years (e.g., Roch and Jaeger 2014).

3.1.3. How Analyses are Typically Reported

Effective mesh size is reported at the defined unit of analysis (e.g., a hexagon, a township, a watershed), and thus, provides a single average value for the region being assessed. As a consequence, if the unit of analysis gets larger, landscape changes also need to be larger to have a measurable influence on effective mesh size values. As well, for large analysis units, important spatial patterns of fragmentation and the role that aggregation of habitat patches plays in determining connectivity is not accounted for in the calculation. Therefore, as a way to better understand where fragmentation is occurring and may be affecting connectivity on the landscape, projects tend to assess mesh size at multiple scales and using multiple definitions of fragmentation geometries.

Effective mesh size has value as an initial or preliminary assessment of the effective area of continuous natural cover within a particular landscape, and can be used to generally compare different areas (e.g., Jaeger et al. 2008; Jaeger et al. 2011); however, areas being compared must have had their natural cover and fragmentation geometries defined using the same data and definitions in order to make the metric values comparable across space and time.

3.1.4. Applications Overview

Effective mesh size has been applied as a metric to quantify fragmentation in several jurisdictions worldwide. All of these projects highlight the need to explore several different fragmentation geometries and that the appropriate choice for a fragmentation geometry is dependent on the context and objectives of the study. Representative projects include:

- Moser et al. (2007) calculated effective mesh size for the entire region and for individual municipalities of South Tyrol, Italy. This analysis primarily highlighted the benefits of applying the modified CBC method, but also allowed comparison of municipal levels of fragmentation;
- Girvetz et al. (2008) applied effective mesh size to assess fragmentation for the state of California. Four different fragmentation geometries were applied to six different reporting units to assess fragmentation and to compare regions and provide a current condition to which future development scenarios could be compared;
- Jaeger et al. (2008) assessed fragmentation of Switzerland by applying four different fragmentation geometries to two different reporting units. They compared the different results and found that the most appropriate choice of fragmentation geometry depends on the context and objectives of the study;
- Current levels of fragmentation were assessed in Europe and compared among regions and analyzed alongside socioeconomic and geophysical variables to understand the relevant contributors to fragmentation in each region and to identify areas for prioritising management action (Jaeger et al. 2011). The 2011 levels of effective mesh size were also meant to serve as a baseline level to which future assessments could be compared;
- The province of Ontario is using effective mesh size as the terrestrial landscape fragmentation indicator to assess the state of biodiversity in the province (Ontario Biodiversity Council 2015). Mesh size was assessed for most ecodistricts in the Mixedwood Plains Ecozone and considered all roads, other infrastructure, urban areas, agricultural areas, and extraction areas as fragmentation barriers. Analysis is ongoing, but the province hopes to use effective mesh size to monitor trends in fragmentation across the province;
- Walz (2015) assessed fragmentation with effective mesh size for rural distracts and urban municipalities in Germany using roads, railways, canals, and settlement areas as fragmentation geometries. The assessment was used to generally assess spatial patterns of remaining intact open space in the country;
- Roch and Jaeger (2014) applied effective mesh size to assess the degree of grassland fragmentation in the Canadian prairies. They applied four different fragmentation geometries to five types of reporting units to understand the level of fragmentation and suggested the approach as a suitable way to monitor grassland fragmentation long-term.

3.1.5. Limitations and Considerations

The most important limitation and critique of effective mesh size is that is an *indirect* measure of structural connectivity (i.e., this approach measures fragmentation, not connectivity). Further, because this approach does not consider species movement or behaviour when dispersing between patches, or the affect that spatial arrangement of patches has on connectivity (e.g., the distance between or configuration of patches), it is not a measure of functional connectivity. In addition, this metric is highly correlated with habitat abundance and is unable to differentiate between landscapes of different aggregation levels; therefore, it is likely not as effective as functional metrics for reflecting changes in aggregation or layout of habitat (Wang et al. 2014).

As well, at a regional scale, effective mesh size is insensitive to small changes to or small removals of patches, and the metric is also limited in that it is not as effective at capturing nuanced changes to the landscape (e.g., improvements to areas where the land cover type is modified to become less resistant to movement). Further, for a score to improve (i.e., increase the effective mesh size value), a jurisdiction would need to remove fragmentation geometries (e.g., the removal of roads or farmlands), which would either be a very significant process and/or unrealistic.

Finally, the quantification of effective mesh size is ultimately sensitive to the definition of fragmentation boundaries and the accuracy, completeness, and consistency of the data sets used to represent the fragmentation geometries. For example, using refined datasets on roads, Pătru-Stupariu et al. (2015) assessed effective mesh size for Romania and quantified a value of 50 km^2, which was in very strong contrast to the value of 1,700 km^2 calculated in a previous European Environment Agency assessment (Jaeger et al. 2011). This highlights the need for accurate and consistent datasets if relying on the metric as an indicator of change through time, or if being used to compare regions.

3.1.6. Potential Use as a BMF Indicator in Alberta

Effective mesh size has been previously explored as a potential structural connectivity indicator for regional planning Alberta (e.g., BMF science support methods document, n.d.; Olson 2014; ABMI 2016). Specifically, effective mesh size was calculated for the South Saskatchewan Region by using the 2010 ABMI Human Footprint Inventory to define patches and fragmentation geometries in two ways (BMF science support methods document, n.d.). In the first calculation, all human footprint types were fragmentation barriers and natural patches were all other remaining areas. In the second calculation, the BMF STC defined fragmentation barriers as specific types of human footprint that were considered to be significant barriers to landscape-level ecological processes. The two results were then averaged to provide a connectivity indicator for the region.

In Olson (2014), 1 km^2 hexagon tiles were used to calculate effective mesh size across the entire province, in which natural cover was assumed to be any area not covered by certain types of human footprint and two versions of fragmentation geometries were used to calculate the metric. The 2012 Wall-to-Wall Human Footprint layer was used to calculate effective mesh size layers in two ways. In Version 1, natural cover was fragmented by all water bodies and all types of human footprint except for cutlines (e.g., roads, agricultural fields, etc.). This represented a ‘maximally fragmented’ analysis appropriate for organisms highly sensitive to fragmentation at a small scale. In Version 2, natural cover was fragmented by lakes and major rivers and all non-linear human footprint (e.g., all human footprint except roads, seismic lines, pipelines, rail lines). This version represented a fragmentation level appropriate for larger, less sensitive species that use the landscape over a broader spatial scale while avoiding areas of substantial human disturbance. These two layers were updated in 2016 by the ABMI to correct for issues associated with GIS processing of the human footprint layer (ABMI 2016). The two province-wide effective mesh size layers are currently freely available from the ABMI as spatial data layers that can be used to measure habitat fragmentation.

Supplementary analyses assessed the effect of hexagon size on effective mesh size and the ability for the metric to detect change for different land management scenarios at the regional scale by determining the mean effective mesh size across all hexagons in that region. Results indicated that the choice of hexagon size can have a large effect on the assessment outputs, and that there is some uncertainty in how effective mesh size changes in response to different land management scenarios.

3.2. Circuit Theory Connectivity Modelling

3.2.1. Overview

Circuit theory is a special type of network model that assesses the connectivity of landscape as an electric circuit, in which ecological flow or movement is modelled as current flowing across a conducting surface (McRae et al. 2008). A resistance layer is used as the conducting surface, in which each cell is a resistor that determines the flow of current to the neighbouring cell. Current is added at source patches or nodes and flows toward termini patches through the circuit through paths that minimize overall resistance. The output is a continuous surface that predicts the probability of movement for all possible paths in the landscape, with the assumption that the individual has limited knowledge of the surrounding landscape and that movements through the landscape are random (Dickson et al. 2019).

3.2.2. Method

The traditional approach to circuit theory requires that habitat patches or core areas be identified, which serve as source and ground nodes (i.e., termini), and also requires the development of a cost surface raster to use as an input as the resistance layer. The flow of current across the landscape is then modelled, starting from the source and moving from cell to cell based on the resistance values that are encountered. The result is a continuous raster current density map that is used to analyze connectivity.

To circumvent the need to define habitat patches for a particular species, Koen et al. (2014) developed a multi-species, omni-directional approach that that was applied to the Algonquin to Adirondack region in eastern North America. This approach applied a cost surface that represented general permeability to the landscape for animals that avoid unnatural landscape features, and modelled connectivity across the region by placing nodes around the study area instead of designating habitat patches.

A handful of software packages exist to apply circuit theory. Circuitscape (Shah and McRae 2008) and the more recently developed GFlow (Leonard et al. 2016) are both freely available and have been applied to projects of various scales. The software package Linkage Mapper (McRae and Kavanagh 2011) combines circuit theory alongside several other approaches (e.g., least-cost corridor mapping) for mapping and prioritization of wildlife habitat corridors.

3.2.3. How Analyses are Typically Reported

The most common products used by those who apply a circuit theory approach is the cumulative current density map that is generated as part of the analysis. In this raster map, each cell represents a current density value, which is the sum of current flow across all node pairs. Current density is a prediction and is proportional to the net movement probabilities or flow of random walkers through a given grid cell, where higher current density suggests an area through which successful dispersers are more likely to travel. Greater connectivity is predicted when a greater number of connected pathways are available. Locations where current density is the highest are often associated with locations that are ‘pinch points’, which are areas that are bottlenecks or where alternative pathways do not exist. Thus, current density maps are useful for identifying which areas may contribute most to connectivity between focal points (McRae et al. 2008) and in providing estimates of regional patterns of connectivity (Dickson et al. 2013).

The current density map provides a complete overview of predicted connectivity; however, a thresholding approach has also been applied to suggest specific locations that are potentially important to connectivity in the study area (Bowman and Cordes 2015). This approach assumes that high current density accurately predicts the likelihood of animal movement, and is dependent on testing different thresholds and choosing a threshold that captures locations of high connectivity in a meaningful way.

A metric that has been commonly used to asses connectivity between patches in a landscape is resistance distance (or effective resistance) (McRae and Beier 2007; Marrotte et al. 2017; Dickson et al. 2019). Resistance distance provides a pairwise distance-based measure of isolation among nodes. Conceptually, resistance distance is similar to least-cost distance, and when there is only one path between nodes, the two will be equal (Marrotte and Bowman 2017). However, when there is more than one path between nodes, resistance distance will be the average least-cost distance of all of these pathways. Resistance distance has been applied as a variable in models to test hypotheses of species movement and patterns of gene flow (e.g., in Marrotte and Bowman 2017), and has also been used as an input into graph theory metrics to quantify landscape connectivity.

3.2.4. Applications Overview

In the roughly 10 years since it was first presented, circuit theory has been quickly adopted and has been applied widely to understand and map patterns of connectivity. The majority of major, broad-scale projects have used circuit theory predictive maps to characterize connectivity and inform conservation planning, such as in identifying areas predicted to be important to connectivity and candidate areas for corridor allocation or expansion (e.g., Pelletier et al. 2014). Representative examples include:

- Dickson et al. (2013) applied circuit theory estimate regional patterns of connectivity for pumas (*Puma concolor*) in the Southwestern United States, and used maps of current flow to highlight areas important for keeping the network of habitat patches connected and to highlight pinch points along major interstate highways. It was further suggested the maps could be used to target finer-scaled analyses and to target protection of landscape features that facilitate dispersal;
- Proctor et al. (2015) applied circuit theory to grizzly bears to predict pinch points and linkage areas within least-cost corridors that were calculated from a cost layer based on a habitat suitability model. Predicted linkage areas were compared to bear highway crossing activity, and it was suggested that the linkage locations provide a opportunity to prioritize management;
- Brodie et al. (2015) applied circuit theory in Borneo to predict connectivity within least-cost corridors for individual and combinations of species and compared the overlap of predictions. Current density maps were used to complement the corridor analysis by showing locations within the corridors that had the highest cumulative current flow;
- Dickson et al. (2016) applied circuit theory to estimate patterns of ecological flow among existing protected areas (PAs) in the Western United States. Current maps were used to determine which PAs were most likely to maintain connectivity, and to suggest locations where land could be allocated to enhance connectivity;
- As part of a regional connectivity analysis of the Lower Hunter region of Australia, circuit theory was used to compliment a regional graph theory analysis by modelling local-scale connectivity in a small area that had been identified by graph theory as a possible rehabilitation site for increasing connectivity across the study area (Lechner and Lefroy 2014). The local-scale current density maps were used to assess locations of redundancy or potential bottlenecks to further inform selection of sites for rehabilitation;
- Bowman and Cordes (2015) applied the omnidirectional technique developed by Koen et al. (2014) to model multispecies habitat connectivity across the Great Lakes Basin in Ontario and used the cumulative current maps to help identify potential highly connective movement corridors that will be important for landscape management;

- The omnidirectional technique was also applied by Pelletier et al. (2014; 2017) to assess regional and national predictions of forest connectivity, and was used to identify the locations of potential areas important for conservation and possible pinch points.

3.2.5. Limitations and Considerations

It is important to recognize that the predictions from circuit theory are not precise estimates of real-world movement, but rather a perspective on *potential* movement patterns. Further, the predictions are for random walkers moving across the landscape and flow between nodes is symmetrical (i.e., exactly the same in both directions), which may not reflect all species or situations. As well, while this method is very effective at identifying pinch points and alternative pathways for movement, interpretation of predictions for circuit theory models can be difficult. For example, higher current may flow through a cell for several reasons, including: 1) resistance through the cell is low; 2) the majority of paths are forced through the cell because of high resistance elsewhere, or; 3) the analysis is spatially constrained. Further, lower current through a cell may imply either high resistance in the input layer or that there are many equally good alternate paths for movement (Wade et al. 2015; Pelletier et al. 2017). Additionally, predictions must be considered carefully for small patches, as a 'halo effect' is a common artifact around small patches; here, the small surface area of the patch results in higher modelled movement probabilities because there are fewer areas to enter and exit the patches, which can be mistakenly identified as a pinch point.

In addition to being difficult to interpret, predictions from circuit theory are highly sensitive to the resistance values chosen, the degree of contrast between values for features, and the spatial resolution and degree of spatial aggregation used. As well, the circuit theory approach may be more applicable to certain species and certain landscapes (e.g., McClure et al. 2016), especially considering that there is no dispersal distance threshold that can be applied to the modelling, which effectively makes all nodes "reachable". In cases where a maximum dispersal distance is required, a mask or corridor is used to constrain the circuit theory modelling to an ecologically relevant area (e.g., McRae and Kavanagh 2011; Lechner et al. 2016). Marotte et al. (2017) found that performance of current density was dependent upon landscape pattern and suggests that current density predictions may be more relevant when habitat is less abundant.

While new software has been developed to help overcome the known computational challenges associated with circuit theory models (Leonard et al. 2016), large-scale analyses are still somewhat limited by available computational resources (Lechner et al. 2015), and even for those projects with access to the largest supercomputers, most projects ultimately are forced to downscale data or segment the study area into smaller components to run analyses successfully (e.g., Bowman and Cordes 2015; Pelletier et al. 2014; Pelletier et al. 2017). It is not surprising then, that many regional connectivity projects use circuit theory not as part of their broad-scale mapping, but rather, as complementary finer scale, local analyses, often in combination with other approaches, such as least-cost corridor mapping to direct and implement linkages (e.g., Proctor et al. 2015; Brodie et al. 2015; McClure et al. 2016).

Importantly, circuit theory has not been applied to compare or quantify changes in connectivity over time, or to assess the increase or decrease in connectivity in response to landscape change. McClure et al. (2017) used circuit theory to identify future barriers to movement in the American Southwest; however, instead of comparing present-day and future current maps, this approach overlaid proposed future road development on a present-day current map to predict where connectivity may be impacted. Comparisons of a time-series of circuit theory outputs are lacking, likely due to the fact that circuit theory predictions are relative probabilities of movement that cannot be directly compared. Further, circuit theory model predictions are difficult to interpret because areas of low current density do not always correlate to area of low connectivity and pinch points do not necessarily indicate locations with high connectivity and high rates of species use; thus, subsequent predictions of the same landscape may generate unintuitive predictions. For example, if an area identified as pinch point is widened through targeted management action, the current density in that location will decrease, and this area could be mistakenly interpreted as having lower importance during subsequent analysis, if current density is interpreted directly as importance to connectivity. Therefore, circuit theory's primary strengths and benefits may be its ability to identify bottlenecks for movement, and in spatially prioritizing locations where conservation action and resources are best directed to improve or conserve connectivity, rather than in assessing change in connectivity through time. Alternatively, the interpatch resistance distances generated from a circuit theory analysis can be applied as an interpatch distance input in other quantitative approaches to calculate metrics, such as with graph theory.

3.2.6. Potential Use as a BMF Indicator in Alberta

Recently, researchers at the University of Toronto have applied an agnostic species approach in which human impact and intensity of use were used to model landscape resistance, and probability of movement across the entire province was predicted. This approach proposes to use current density as a score of connectivity at the pixel level, and to calculate mean scores at different sub-division levels (e.g., LuF planning regions, municipal districts, townships). While further assessment and decisions are required, these mean scores have been put forward as a metric that could be used in the BMF as a connectivity indicator. Alternatively, a thresholding approach could be used to classify pixels by connectivity importance; this method would assume that pixels with high current density values are the most important to connectivity. The approach is still being tested and refined to understand which combination of resistance values, output values, and thresholds most meaningfully predict connectivity at the provincial- and finer-scales.

Other applications of circuit theory within Alberta that have been used in a prioritization and planning context include:

- Modelling of potential connectivity for four Alberta species (mule deer, grizzly bear, pronghorn, and rattlesnake) to identify and prioritize road sections where wildlife connectivity and potential for traffic collisions may be high (Lee et al. 2019);
- Predictive modelling of elk in Southwestern Alberta (Paton 2012);
- A multispecies analysis of the City of Calgary to evaluate connectivity of the existing municipal parks network (Fiera Biological Consulting 2017).

3.3. Least-cost Methods

3.3.1. Overview

Least-cost analyses are the most commonly applied approach for analyzing functional connectivity (Correa Ayram et al. 2016). Similar to circuit theory, movement across a resistance surface between patches is modelled; however, least-cost modelling assumes that individuals have complete knowledge of the landscape and will choose a path or route that minimizes the ecological cost to travel between patches (Adriaensen et al. 2003; Rayfield et al. 2010; Correa Ayram et al. 2016). Most commonly, single paths between patches are generated, which represent the lowest cumulative cost to travel between a given patch pair; however, other approaches that more generally predict areas that support connectivity have also been developed and are growing in popularity.

3.3.2. Method

A traditional least-cost analysis requires that habitat patches or core areas be identified, which serve as the start and end points to calculate the predicted movement path, and that a cost surface be created that models permeability of the landscape. Then, an algorithm assesses the values assigned to each cell in the resistance surface to determine the path that results in the lowest cumulative 'cost' of cells combined

(Rudnick et al. 2012). For this single path, the distance between patches can be calculated as the total path length or the cumulative cost distance, which provides a measure of effective distance for each patch pair. Shorter effective distances are assumed to be of higher connectivity, since they are effectively closer. In scenarios for which a single path between patches is not suitable or realistic to describe animal movement (Adriaensen et al. 2003; Cushman et al. 2013), least-cost analysis has been adapted by using thresholds of accumulated costs to generate least-cost corridors (Pinto and Keitt 2009; WHCWG 2010; McRae and Kavanagh 2011), or by generating dispersal kernels for multiple locations across the landscape and then creating a cumulative surface that predicts the relative density of dispersers across the landscape (Landguth et al. 2012).

Least-cost analysis software is available widely and can be performed in common GIS software packages (e.g., ArcGIS, QGIS), in open source software packages (e.g., Linkage Mapper, UNICOR, LandScape Corridors), and in R (e.g., gdistance, movecost, genleastcost).

3.3.3. How Analyses are Typically Reported

Maps are a common output from least-cost analyses, which are used to identify predicted movement paths or corridors between locations and to prioritize locations for protection or intervention (e.g., Chetkiewicz and Boyce 2009). Cushman et al. (2014) suggest that resistant kernel modelling may be an option for quantifying differences in connectivity between different landscape or over time; however, the extent to what this has been performed successfully is unknown. An intermediary product of a least-cost path analysis, the cost-weighted distance surface can be informative in that it displays the relative resistance between each cell and the most accessible patch, and can be used to evaluate the relative permeability across the landscape as a whole. The effective distance calculated from least-cost paths can also be used as simple metric that provides an indication of patch-level connectivity (i.e., shorter distance equates to higher connectivity), and it is also often used as the distance input into other analyses, such as when calculating graph theory metrics (Galpern et al. 2011; Rayfield et al. 2011; Albert et al. 2017).

3.3.4. Applications Overview

Least-cost modelling has been applied widely in connectivity studies of all scales (Cushman et al. 2013; Correa Ayram et al. 2016). Representative broad-scale analyses include:

- Belote et al. (2016) applied least-cost analysis to generate corridor maps and evaluate connectivity priorities for maintaining a connected network of protected lands across the United States. Their approach used maps of human modification to generate resistance, and large protected areas were designated as core areas;
- Washington State based a statewide connectivity analysis on least-cost corridor analysis of sixteen different species, which provided map predictions of species specific linkage zones between core habitat that were then overlaid to determine areas important for connectivity (WHCWG 2010). These broad-scale mapping efforts are being applied to direct finer-scale studies of connectivity across the state;
- The state of California applied least-cost corridors in a more general, landscape elements-based approach to generate an “Essential Habitat Connectivity Map” that predicts important connectivity areas and areas that are lacking in connectivity (Spencer et al. 2010). This statewide map is being used to plan and prioritize areas for conservation, management, and finer-scale connectivity studies;
- Cushman et al. (2013) used least-cost approaches (factorial least-cost paths and resistant kernel modelling) to predict the location and intensity of use of movement corridors across the American Great Plains for three different species. They compared predicted corridor overlap and identified priority locations for mitigation, restoration, and conservation actions;

- Cushman et al. (2014) applied least-cost approaches (factorial least-cost paths and resistant kernel modelling) to predict locations of highway crossings by American black bears in the Northern Rocky Mountains, USA;
- A species-based approach was applied by Brodie et al. (2015) to assess potential corridors for threatened mammals in Borneo. They found that a multispecies approach that groups ecologically similar, disturbance-sensitive species may result in the most effective corridor designation.

3.3.5. Limitations and Considerations

The calculation and spatial designation of least-cost routes is highly sensitive to input data, spatial resolution, and assigned cost values for cells, which can result in a high degree of uncertainty in results (Adriaensen et al. 2003; Rayfield et al. 2010; Zeller et al. 2012). Further, this type of approach assumes a species has complete knowledge of the landscape and that movement decisions are based on the same preferences used by a species when selecting habitat, and therefore, may confound movement behaviour and resource use (Zeller et al. 2012). Least-cost models have also been criticized for ignoring how animals actually use the landscape, since the approach cannot predict changes in decisions or interactions during the start, middle, and end of dispersal (Sawyer et al. 2011), nor does the approach reveal the behavioural feasibility of using the calculated path (Adriaensen et al. 2003). Consequently, least-cost approaches are best suited to scenarios where species have well defined ranges and predictable movement behaviour, and are less suited to scenarios where species are dispersing, exploring a new landscape, or using the landscape more randomly. Like other predictive approaches, the results should not be interpreted as predicting specific movement routes, but rather, as a reflection of the relative permeability of different areas of the landscape (Singleton and McRae 2013). Alternatively, the interpatch effective distances generated from a least-cost path analysis can be applied as an interpatch distance input in other quantitative approaches to calculate metrics, such as with graph theory.

3.3.6. Potential Use as a BMF Indicator in Alberta

There are many possible ways that least-cost modelling could be adapted into a connectivity indicator for use in the BMFs. For example, a corridor mapping approach could be explored as a way to quantify total permeable area within the region, or resistant kernel mapping could be explored as a way to assess connectivity in a more continuous way as predicted density of dispersers. Because the resistant kernel mapping approach is similar to the circuit theory approach that is currently being explored by the U of T, we present resistant kernel mapping as a potential metric for assessing connectivity in the regional BMFs. We describe this approach in more detail below, and provide a critique of this method in Section 4.

Resistant kernel modelling of the region of interest (here, a LuF region) would calculate kernels for all cells in the region, and the final predictive output would give a prediction of the cumulative density of dispersing individuals for each cell. This mapped output is comparable to the continuous raster output of a current density map. Next, to align with the circuit theory approach, the predicted cumulative density of dispersers raster would be interpreted as a score of connectivity at the pixel level, and this would then be translated into a connectivity indicator by calculating the mean score across the region (or at the scale of the planning region of interest). A version of this approach was applied by The Nature Conservancy (Anderson and Clark 2012) who interpreted the cell values of cumulative density as a measure of "local connectedness" and calculated "mean local connectedness" in the northeastern United States. The optional thresholding technique suggested in the U of T circuit theory approach could also be explored as a way to classify pixel values of local connectedness, and the percent cover of the highest scoring class could be used as an indicator of landscape connectivity. Because it is a predictive mapping approach, this method would need to be validated, tested, and refined to understand which combination of resistance values, output values, and thresholds most meaningfully predict and quantify connectivity at the provincial- and finer-scales.

3.4. Graph Theory

3.4.1. Overview

Graph theory (Urban and Keitt 2001), a branch of mathematics that studies the connections among discrete objects, forms the theoretical basis for the majority of other currently applied models and assessments of connectivity. In graph-based approaches, the landscape and connectivity of patches is represented as a "habitat graph", which is a collection of nodes (patches) and links that connect the nodes. The links between nodes represent the potential for or frequency of movement between patches, and the way in which nodes and links are defined determines the type of connectivity (i.e., structural or functional) being represented (Ricotta et al. 2006; Galpern et al. 2011; Foltête et al. 2014). The connectivity of the graph is measured by quantifying some property or properties of the network. The simplest graphs consider only the presence and absence of links (i.e., connections) between nodes and characterize connectivity based on patterns of connections of nodes (i.e., structural connectivity). More complex graphs, often referred to as network graphs or network analyses, incorporate variation and strength of connections by assigning characteristics to nodes, such as size or habitat quality, and defining weights for links, such as cost distance, which allows connectivity to be characterized based on ecological characteristics of nodes and links (i.e., functional connectivity) (Fagan and Calabrese 2006; Kindlmann and Burel 2008). Graphs can also be directed graphs, in which movement between patches can be asymmetrical. Network analyses are often fused with other techniques, such as least-cost analyses or circuit theory, in which the effective distances between patches become the attributes for the links in the graph (Baldwin et al. 2010; Luque et al. 2012).

Graphs are applied to many different types of connectivity questions, many of which are management and conservation priority based and/or aim to quantify and assess the impacts of management decisions on landscape connectivity (Minor and Urban 2008; Urban et al. 2009; Rayfield et al. 2011; Foltête et al. 2014; Pietsch 2018). Galpern et al. (2011) describe the following nine connectivity questions that can be addressed using a graph theory approach:

- Which areas of the landscape are connected?
- Which areas of the landscape are highly connected?
- How does connectivity differ between graphs?
- What are the critical thresholds at which the landscape is aggregated?
- What are the implications of the network topology for connectivity?
- Which patches are important for connectivity?
- Which patches are important as sources and which as sinks?
- What types of patches are important for connectivity?
- Which connections among patches are important for connectivity?

3.4.2. Method

Performing a graph network analysis requires that the landscape be modelled as a network of nodes connected by links, in which nodes represent habitat patches or core areas, and links are connections between nodes that indicate the potential ability of an organism to directly disperse between the two patches (Urban et al. 2009). Links can be physical connections, such as corridors, or may represent the functional connection between nodes. Accordingly, links are characterized by some measure of distance, which can be defined as Euclidean distance (i.e., straight-line distance) between patches, or as an effective distance that takes into account the variable movement preferences and abilities of species as it moves through different land cover types (e.g., least-cost or resistance distances). Typically, to make the network ecologically relevant, mean dispersal distances are used as a threshold against which interpatch distances are compared and the determination made as to whether or not to assign a link between patches.

Connectivity is then assessed by mathematically testing the properties of the network via a suite of calculated metrics based on the nodes and links (reviewed in Pascual-Hortal and Saura 2006; Saura and Pascual-Hortal 2007; Galpern et al. 2011; Rayfield et al. 2011). Topological metrics only consider the presence/absence of a link between nodes, while weighted indices use the values or attributes assigned to the nodes and links to consider variation and strength of connections locally and throughout the network. Metrics are available to assess the network at different levels; this includes:

- Landscape metrics (i.e., global or network metrics), which assess the network as a whole;
- Component metrics (i.e., cluster metrics), which assess groups of interconnected nodes; and,
- Local metrics (i.e., element or patch metrics), which focus on the properties and importance of individual nodes or links.

An overwhelming array of graph theory metrics exist to quantify movement through the network, determine redundancy of routes, and assess the relative importance and contribution of patches to connectivity of the network. The majority of these have been tested for sensitivity and reliability with regards to quantifying connectivity (Pascual-Hortal and Saura 2006; Saura and Pascual-Hortal 2007; Baranyi et al. 2011; Rayfield et al. 2011), and for a given study a subset of metrics are chosen depending on the goal of the connectivity analysis. Some of the more commonly applied metrics at the landscape-, component-, and local-level are shown in Table 1. The most commonly applied and reliable metrics are included as part of the more common software packages that are used to perform a network analysis, which include Conefor (Saura and Pascual-Hortal 2009), Graphab (Foltête et al. 2012), igraph (Hartvigsen 2011), and grainscape (Galpern et al. 2012).

3.4.3. How Analyses are Typically Reported

A metric is selected to answer a specific connectivity question, and therefore, the quantified metric value is reported and used to characterize the property of the network being that is being assessed. Often, a set of metrics is selected if there are multiple objectives for the analysis, such as when there is a need to measure connectivity properties at different scales (e.g., patch-scale versus network scale). For example, a regional connectivity analysis might use the probability of connectivity index to report on the connectivity at the network level, but may also calculate and report metrics for node and/or link importances to understand what patches and links are the most sensitive or important to the network. In this way, there is a network-level measure that can be used to compare connectivity among different regions or at different time steps (Foltête et al. 2014), as well as patch-level measures that can help to inform planning and to prioritize patches or links for conservation.

While most interest in an analysis is generally associated with the metric values, the constructed network graph visualized as a map can serve as an informative planning tool because it can simply describe the spatial configuration of habitat and illustrate where nodes are clustered or isolated (Galpern et al. 2011). As opposed to the continuous map of values associated with analyses focused on creating a predictive map, a network graph is a diagrammatic vector map with the nodes symbolized as points and links as lines. Symbology is selected to communicate the property or characteristics that the analysis is meant to communicate (e.g., node size to communicate patch size or importance, or line width to communicate link strength or importance), and the diagram can be overlaid onto imagery or other data layers to visually analyze properties of the network.

Table 1. Overview and summary of the more commonly applied graph theory metrics applied in landscape connectivity analyses. Metrics are organized based on the connectivity property they measure (first column) and the spatial scale that they are calculated at (local, component, landscape). Table adapted from Rayfield at al. (2011).

Connectivity Property	Scale Level		
	Local	**Component**	**Landscape**
Route-specific flux (accounts for movements among patches; measures are based on existence, length, or cost of a single route)	Betweenness centrality; Closeness centrality; Node degree; Node depth; Node in degree; Node out degree; Reachability index	Average path strength; Characteristic path length; Component order; Component size; Diameter; Harary index; Path strength; Wiener index	Diameter of largest component; Gamma index; Mean component size; Mean or SD of node degree; Number of components; Order of largest or smallest component; Traversability
Route redundancy (accounts for presence of multiple, alternate routes among patches; measures are based on the number and length/cost distributions of routes)	Commute time; Effective resistance; Network flow; Link redundancy	Clustering coefficient	Meshedness
Route vulnerability (accounts for the degree to which landscape structure funnels or scatters movement; includes interactions and dependencies among paths)	Current density	Reliability; Number of cut nodes; Number of cut links;	Total number of cut nodes; Total number of cut links
Connected habitat area (accounts for net connected habitat by integrating all pathways to describe effective habitat patches)	Dispersal flux; Node area; Modified incidence function; Quality-weighted area	Component area	Area index; Expected dispersal flux; Integral index of connectivity; Probability of connectivity; Equivalent connectivity/area index

3.4.4. Applications Overview

Network graphs have been applied to study connectivity for species of all sizes and scales ranging from beetles (Vasas et al. 2009) to caribou (O'Brien et al. 2006), and have also been applied to understand agricultural crop connectivity and risk of crop pest and disease spread (Margosian et al. 2009). Studies that apply graph theory to particular species are often concerned with assessing local metrics to understand patch importance (e.g., Minor and Urban 2008; Estrada and Bodin 2008; Almpanidou et al. 2014), or to test scenarios of patch removal and quantify changes in short- and long-range connectivity (e.g., Albert et al. 2017, McIntyre et al. 2018).

Graph theory provides a useful compromise between methodological simplicity and ecological relevance that makes it suitable for land planning at broad scales (Foltête et al. 2014; Pietsch 2018), and accordingly, it has been applied in many regional-scale projects to assess connectivity. Multi-species or guild-based approaches are common in these broad-scale studies. Representative analyses include:

- Minor and Lookingbill (2010) assessed protected-area connectivity for small, medium, and large mammals in the three largest biomes in the United States. Network connectivity was quantified using a metric based on a ratio comparing aggregate area within the largest component to total area of reserves in the entire biome. Metric values and the network maps were compared to understand the differences in connectivity among biomes, as well as between the different guilds to understand benefits and challenges to applying an “umbrella” approach;

- Lechner et al. (2016) assessed the connectivity of various “dispersal guilds” in Tasmania, in which habitat and dispersal traits were used to group species, and connectivity of each guild assessed and compared using a suite of graph metrics. Similar studies have been performed in several parts of Australia (e.g., Lechner et al. 2014; Lechner et al. 2015; Lechner et al. 2018);
- Sahraoui et al. (2017) assessed the potential impacts of land cover changes on connectivity for a variety of “virtual” representative species. The probability of connectivity index (PC) was used to compare effects among species globally, and a local metrics were used to compare local effects.

Analyses focused on landscape elements as opposed to focal species are also common. Representative analyses include:

- Goetz et al. (2009) analyzed connectivity within the Northeastern United States by defining core habitat patches using GIS layers and satellite imagery, and weighting links using a cost surface developed from a land cover classification. The graph network was then compared to the existing parks and protected area locations to identify isolated protected areas, as well as core habitat that may provide important connections for exiting protected areas;
- Wimberly et al. (2018) analyzed grassland connectivity in fragmented agricultural landscapes in north-central USA. GIS data layers and airphotos were used map grassland locations, and a suite of graph metrics were used to assess patch-, component-, and network-level characteristics based on different dispersal threshold scenarios. The analysis identified major grassland clusters, stepping stone patches, and “keystone patches”, whose loss would have a disproportionate effect on overall network connectivity;
- McIntyre et al. (2014) used graph theory to model connectivity within and across the main wetland complexes in the Great Plains of North America and tested how connectivity of the network will change in response to climate change. Node importance metrics were used to identify wetlands that are important hubs or stepping stones in the context of climate change, and network path metrics were used to assess change in network connectivity;
- McIntyre et al. (2018) applied graph theory to assess change in connectivity over 27 years for a network of playas (freshwater wetlands) in the southern Great Plains. Eleven metrics were used to assess patch- and network-level changes over time, including degree of connectedness, clustering, path redundancy, node importance, and the amount of reachable habitat as measured by the equivalent connected area index (ECA). The metric comparison quantified the losses in wetland over time and the different impacts that these losses had on connectivity of the network at different scales;
- Santini et al. (2016) and Saura et al. (2017) assessed the connectivity of the network of protected areas worldwide, and compared terrestrial connectivity across countries, continents, and ecoregions when considering a range of dispersal distances. Santini et al. (2016) used the probability of connectivity index (PC) to show that national networks tended to have higher connectivity than continental networks, indicating that transboundary connectivity is often weak and should be improved. Saura et al. (2017) applied the probability of connectivity index and the equivalent connected area index (ECA) to show that the current spatial arrangement of protected areas has resulted in a network that is not well connected, and that the connectivity of protected areas varies largely across ecoregions.

3.4.5. Limitations and Considerations

Modelling and organizing a landscape as a habitat network allows for the incorporation of diverse data types and information on species’ movement and behaviour (Rayfield et al. 2011), and is an efficient and flexible way to assess connectivity at different scales (Urban et al. 2009). However, defining and building the network requires serious consideration of the goals of the connectivity analysis, and has many key decision points. Performing a network analysis includes comparable challenges to most other connectivity approaches, such as deciding on what landscape features the nodes represent, which ecological process the links characterize, the rule that determines whether nodes are connected to one another, and deciding on what metrics will be calculated. Notably, the approach is well-reviewed and guides exist to aid in the application of the graph-based approach for planning and decision-making (e.g., Baranyi et al. 2011; Galpern et al. 2011; Rayfield et al. 2011; Foltête et al. 2014), and the flexibility of the approach allows for the integration of other analytical approaches, such as circuit theory (e.g., Rayfield et al. 2016) or least-cost modelling (e.g., Lechner et al. 2015). Maps produced from a network analysis are not a continuous prediction surface of connectivity, and therefore, might not have the visual appeal of some other approaches, but network maps can still quickly and simply aide in identifying components (clusters of connected patches), as well as identify where there are gaps in connectivity or breaks in the network.

Similar to many other popular connectivity approaches, network models can be constrained by computational capacity, especially for broad-scale analyses with tens of thousands of nodes and links. Especially for models that want to incorporate distances calculated from a resistance layer, the computational challenges are only compounded, since calculating these distances can be very time consuming. The network models can be simplified by adjusting the minimum patch size used, by using Euclidean distances, or by creating simplified network representations, such as by using a minimum planar graph (Fall et al. 2007; Galpern et al. 2011); however, the effect that any simplifications have on the realism of the model and the information provided from the analysis, must be carefully considered.

3.4.6. Potential Use as a BMF Indicator in Alberta

Unlike the potential proposed approaches for circuit theory and least-cost modelling, the graph theory approach requires that the region of interest (here, a LuF planning region) be modelled as a defined network of nodes and links. One advantage of graph theory is its flexibility; there are a number of ways that the nodes and links could be defined, and the nodes and links weighted, thereby allowing for multiple scenarios to be considered and evaluated. For example, different patch definitions could be used to account for the habitat patch size and movement requirements for different regional species of interest or species at risk. A graph theory approach can also integrate and analyze the ways in which different features on the landscape (e.g., roads versus agricultural fields) impact connectivity.

Given the inherent flexibility in how connectivity can be evaluated using graph theory, there are multiple different metrics that can be selected and a wide range of different ways of parameterizing the model; thus, for the purpose of critiquing and comparing graph theory relative to the other approaches presented in this report (see Section 4), we must first define one possible scenario that could be assessed using a graph theory approach. In this graph theory model scenario example, nodes are defined as all natural habitat patches (i.e., no or low human footprint) above a certain relevant threshold size (e.g., 1 ha), and links are created between patches for a relevant maximum dispersal distance for species of interest in the region (e.g., 10 km). To assess functional connectivity, a resistance layer is used to calculate effective distances between all patches connected by links. Effective distances between nodes could be calculated from least-cost or circuit theory model outputs. Input layers are then used to quantify the metrics that reflect the particular components of connectivity that are most relevant to the objectives of the analysis. If the primary objective is to quantify connectivity of the network at a landscape-scale, graph theory provides a variety of landscape-level metrics that could be considered (see Table 1).

A good candidate metric for the purpose of assessing regional landscape-level connectivity in Alberta is the probability of connectivity (PC) index (Saura and Pascual-Hortal 2007), which has been applied to assess change in connectivity in many studies (e.g., Saura and Pascual-Hortal 2007; Avon and Bergès 2016; Sahraoui et al. 2017). This index is a measure of functional connectivity that combines attributes of patches (e.g., area or patch quality) with information on the probability of dispersal between patches to give a standardized score that ranges from 0 to 1. The standardized score output from the metric calculation would allow for the establishment of a baseline score that could be compared over time and across regions. Alternatives to the PC index that would also allow for comparison over time include: the equivalent connectivity (EC or ECA) index (e.g., Saura et al. 2011; Rayfield et al. 2016; Albert et al. 2017; McIntyre et al. 2018), which is reported in area units and could be used to describe percent change in connected area over time, and; the integral index of connectivity (IIC) (e.g., Lechner et al. 2015), which is similar to the PC index and ranges from 0 to 1, but is a structural connectivity metric that simplifies connections between patches into yes versus no, rather than using distance between patches to weight the likelihood of patches being connected. Similar to the approach used by McIntyre et al. (2018), additional metrics could be selected and calculated to assess node and link importances (e.g., betweeness centrality, flux, number of cut nodes and cut links), which would complement the landscape-level index being used and provide information on landscape connectivity for the region in different ways and at different scales.

4.0 Assessing Indicators

In Section 3, a set of potential connectivity approaches for creating a measure or applying a metric that can be used as a connectivity indicator in Alberta's regional BMFs was identified. Of these approaches, effective mesh size has previously been explored and considered as an indicator of connectivity, and circuit theory mapping is currently being examined as a potential indicator of connectivity by researchers at the University of Toronto. In addition to these approaches, least-cost analysis and graph theory have been presented as potential approaches that could be used to develop an indicator for connectivity because they are applied widely to model, assess, and quantify connectivity. For these two alternative approaches, possible ways of applying the approach to assess connectivity were presented and described in sections 3.3.6 and 3.4.6 to provide a way to critique the approach for developing a BMF indicator.

In this section, each of these approaches and their respective potential BMF connectivity indicator is assessed and critiqued. As part of this assessment, each approach is critiqued generally with regards to its ability to provide a reliable and robust connectivity indicator, and more specifically with regards to the ability of the proposed indicator to function as a connectivity indicator as part of the BMFs in Alberta.

We defined the following evaluation questions that will be used to critique the suitability of each of the four previously descried connectivity assessment approaches. These criteria reflect the desirable properties that a connectivity index/indicator would ideally fulfill to be adequate for conservation and change analysis applications (Saura and Pascual-Hortal 2007), while also reflecting the unique and desirable criteria that must be satisfied in order to be a meaningful and relevant BMF indicator:

1) Does the approach assess structural or functional connectivity?
2) Is the approach able to produce a single quantified value at the landscape level?
3) If so, does that value have a predefined and bounded range of variation?
4) Has the approach been applied to broad-scale assessments?
5) Has the approach been applied to assess change in connectivity over time or to assess different land use or management scenarios?
6) Is the approach sufficiently sensitive to detect changes in land use and management?
7) How would the approach accommodate analysis of a historic reference condition?
8) Can the approach be adapted to accommodate regional differences? In other words, can it be adapted to reflect regional scale biodiversity and the specific vulnerable aspects of biodiversity in different planning regions?

9) What are the data requirements of the proposed approach?
10) To what degree is the approach (or components of the approach) based on expert-opinion or subjective decisions?
11) How computationally expensive/demanding is the approach?
12) How complex is it to use the approach to measure and monitor connectivity over time?
13) How approachable, understandable, and communicable is the approach and its results to different stakeholders?
14) How does the approach complement the Tier 1 indicator of amount of native or natural cover?
15) Are there opportunities to apply the approach or its outputs in other ways?

In Table 2, each approach is briefly described, and its potential for use as the approach to provide a metric for use as a BMF indicator is assessed based on the above questions. The last row of the table provides an overall assessment and conclusion of the connectivity approach based on all of the criteria considered together. In Table 3, metrics that come from each approach that could potentially be applied as a connectivity indicator in Alberta are assessed using the evaluation criteria presented above, with the results of the assessment presented in a simplified, comparative "report card" style overview. Each of the potential metrics evaluated in Table 3 are described in detail in Section 3 of this report, and specifically, within each subsection that describes and critiques the "Potential Use as a BMF Indicator in Alberta".

The summary presented in Table 3 can be used to assess each potential metric relative to the evaluation criteria presented above; however, the selection of the "best" metric for use in Alberta may differ depending on which of the evaluation criteria have the highest importance or are given the greatest weighting in the metric selection process. When all of the evaluation criteria presented above are considered equally, the three graph theory metrics meet all of the evaluation criteria requirements to an acceptable level. Further, graph theory has been extensively used by academics and practitioners to assess change in connectivity over time, which is an important criterion for the selection of a BMF connectivity metric. The other metrics examined in this report are not as well-suited to assessing change through time, and also provide other challenges, such as high data or computational requirements, or not providing a standardized (and thus comparable) output value. Of the three graph theory metrics considered in this report, the most appropriate metric for use as a BMF indicator depends upon specific priorities and objectives (e.g., preference of a structural or functional metric) and the input data sources that are available for the analysis; therefore, it is difficult to specify which of the three graph theory metrics would be best suited for use as a BMF connectivity indicator.

Table 2. Assessment of the four potential connectivity approaches and their potential to provide an indicator for use in the BMFs.

Evaluation Criteria	Effective Mesh Size	Circuit Theory Modelling	Least-cost Methods	Graph Theory/Network Analysis
Brief description of method	Effective mesh size is a metric developed to quantify landscape fragmentation for an area that describes the average size of an unfragmented area in a study area.	Circuit theory predicts landscape connectivity by modelling the landscape as an electric circuit. Mapped outputs of current density reflect predictions of locations for probability of movement of dispersers.	Least-cost methods determine the most permeable or lowest cost movement routes for a given landscape. Resistant kernel modelling generates a continuous map of predictions of cumulative density of dispersers for each cell.	A branch of mathematics concerned explicitly with connectivity. Models the landscape as a network of nodes and links and then measures properties of the network with patch-level, cluster- or component-level, and network-level metrics.
1. Does the approach assess structural or functional connectivity?	The metric quantifies landscape fragmentation, which is a proxy for structural connectivity of the landscape.	Can model structural or functional connectivity. The U of T approach would be considered a more structural approach, although this is somewhat debateable. Some suggest the "naturalness" approach is a "relaxed" definition of functional connectivity, while others argue this is a structural connectivity approach because it does not specifically account for species habitat preferences and movement behaviour.	Can model structural or functional connectivity. Most typically, least-cost approaches are based on species-based resistance layers and species habitat locations, which would imply a functional approach. However, a “naturalness” approach can also be applied to model structural connectivity. Similar definition arguments apply as for circuit theory if the resistance layer is based on "naturalness", rather than species habitat preferences and movement behaviour.	The approach can assess structural or functional connectivity depending on how the network model is defined and what metrics are selected. For example, the metrics total number of links (L) and the integral index of connectivity (IIC) quantify connectivity based on the presence of physical linkages between all patches, whereas the metrics Probability of Connectivity index (PC) and the equivalent connectivity index (EC) weight links based on distance and dispersal probabilities, and thus consider both habitat amount and how reachable that habitat is.
2. Is the approach able to produce a single quantified value at the landscape level?	Yes. Effective mesh size is reported as the average patch area for an unfragmented patch in a study area.	Yes, as a derived secondary product. The continuous map of values must be summarized in some way to give a single value. For example, a mean score approach gives the average connectivity score for the region. Alternatively, a threshold approach could be used to identify areas of predicted high connectivity, which then could be used to calculate percent cover of predicted or potential high connectivity areas.	Yes, as a derived secondary product. The continuous map of values must be summarized in some way to give a single value. For example, a mean score approach gives the average local connectedness for the region. Alternatively, a threshold approach could be used to identify areas of predicted high local connectedness, which then could be used to calculate percent cover of predicted high connectivity areas.	Yes. Network-level metrics produce a single value as their output. For example, PC is a probability that ranges from 0 to 1.

Continued…

Table 2 *continued*. Assessment of the four potential connectivity approaches and their potential to provide an indicator for use in the BMFs.

Evaluation Criteria	Effective Mesh Size	Circuit Theory Modelling	Least-cost Methods	Graph Theory/Network Analysis
3. If so, does that value have a predefined and bounded range of variation (independent of the landscape being assessed)?	No. The range of values is 0 (complete fragmentation) to the area of the study area. Thus, larger analytical units will tend to have larger effective mesh size. A standardized assessment unit (e.g., hexagon) can be used, but sizes must tested be to produce the most meaningful results.	No. Current density is a relative probability of potential movement or connectivity, and therefore, values are specific to the particular landscape being assessed and the resistance layer being used.	No. Cumulative density of dispersers does not have an upper range, and the values need to be classified into local connectedness scores; therefore, values are specific to the particular landscape being assessed.	Depends on the metric; some metrics are simply descriptive and are particular to the landscape being assessed and others are standardized and allow for broader comparisons. For example, PC is a standardized metric that ranges from 0 to1.
4. Has the approach been applied to broad-scale assessments?	Yes (see Section 3.1.4).	Yes (see Section 3.2.4).	Yes (see Section 3.3.4).	Yes (see Section 3.4.4).
5. Has the approach been applied to assess change in connectivity over time or to assess different land use or management scenarios?	Yes. Is currently applied as an indicator of fragmentation in many European countries and is being used to assess change in fragmentation over time. Has been applied to compare scenarios of road fragmentation.	Partially. Land use change scenarios have been overlayed onto a static current density map to compare pinch points or areas of predicted high connectivity that may be impacted by development. Comparing current density maps over time is not suggested, since outputs can be unintuitive (e.g., widening an area around pinch point will reduce the current density in this area, which will appear as a reduction in connectivity).	Partially. Least-cost outputs generated from resistance layers based on current land use and future land use scenarios have been compared to assess impacts on the potential habitat connectivity of different species (Albert et al. 2017; Kaim et al. 2019).	Yes. Suggested specifically for this purpose (Saura and Pascual-Hortal 2007; Urban et al. 2009; Galpern et al. 2011; Rayfield et al. 2011).
6. Is the approach sufficiently sensitive to detect changes in land use and management?	Depends on the unit of analysis. The larger the analytical unit the less likely small changes will be detected. Change is dependent on definition of fragmentation geometries - the metric only accounts for complete changes to or from a barrier (i.e., cannot assess changes to landscape features in which they become more or less permeable).	Unknown. In theory, changes in land use and management would be reflected in the resistance layer, which would affect the current density map predictions, but there is uncertainty as to how these map predictions would be interpreted or quantified.	Yes. Changes in land use and management would be reflected in the resistance layer, which would affect the resistant kernel predictions. As long as the same thresholds were applied, the results would allow comparisons.	Yes. Metric values respond to additions or removal of patches, additions or removal of links, changes in strengths of links (e.g., change in effective distance between patches), and changes to patches. The sensitivity of the approach is somewhat determined by the size of the study area and the definitions of nodes and links when building the network.

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Table 2 *continued*. Assessment of the four potential connectivity approaches and their potential to provide an indicator for use in the BMFs.

Evaluation Criteria	Effective Mesh Size	Circuit Theory Modelling	Least-cost Methods	Graph Theory/Network Analysis
7. How does the approach accommodate analysis of a historic reference condition?	Reference condition could be defined either as the area of the region of interested (i.e., assumes the area was completely intact historically), or, if large water bodies and other inhospitable land cover types are considered fragmentation geometries, then effective mesh size could be calculated based on this, and the result would be the reference value.	Unknown. In theory, a resistance layer could be calculated reflecting a historic land cover without human footprint or impact, and circuit theory could be modelled on this. However, it is unclear if the output would be meaningfully comparable to “present day” analyses, since an intact landscape with many equally good alternate paths for movement will result in lower current values (i.e., the current density map would not show high connectivity across large low resistance areas) (Wade et al. 2015; Pelletier et al. 2017).	Somewhat unknown. In theory a resistance layer could be calculated reflecting a historic land cover without human footprint or impact, and resistant kernel mapping could be modelled on this. Presumably, prediction maps could be compared, as long as the same thresholds were used to define areas of high connectivity. However, some testing would need to be performed to understand if the approach provides meaningful results.	Reference condition could be defined assuming the area was completely intact historically, which for the PC metric would give the maximum value of 1, or, if large water bodies and other inhospitable land cover types are considered barriers, then the network nodes and links could be defined based on this, and the resulting PC metric value would be the reference score.
8. Can the approach be adapted to accommodate regional differences?	Yes. Fragmentation geometries and natural patch areas could be defined based on focal areas or species that are of interest to that region.	Yes. Nodes and/or resistance layers could be developed to reflect focal areas or species that are of interest to that region. This would generate a current density map or maps specific to that region.	Yes. Core areas and/or resistance layers could be developed to reflect focal areas or species that are of interest to that region. This would generate a resistant kernel map or maps specific to that region.	Yes. Nodes, links, dispersal thresholds, and effective distances can be defined to reflect focal areas or species that are of interest to that region. This would generate a network map or maps specific to that region.
9. What are the data requirements of the proposed approach?	An accurate land use/land cover layer, from which fragmentation geometries are defined; the patches that remain after all fragmentation geometries are removed are the patch areas used to calculate the metric.	A resistance layer with cell values based on human footprint and intensity of use. Nodes are based on the omni-directional approach, which places nodes along the buffered perimeter of the study area.	A resistance layer with cell values that reflect permeability to movement. The U of T resistance layer could be used. Resistant kernels are then calculated for all cells across the surface and summed.	Nodes (core habitat locations) would be naturalness-based. Links would be effective distances between all connected patches calculated using an existing resistance layer (e.g., the U of T layer).

Continued…

Table 2 *continued*. Assessment of the four potential connectivity approaches and their potential to provide an indicator for use in the BMFs.

Evaluation Criteria	Effective Mesh Size	Circuit Theory Modelling	Least-cost Methods	Graph Theory/Network Analysis
10. To what degree is the approach (or components of the approach) based on expert opinion or subjective decisions?	Low to moderate. Decision points include: determining the unit of analysis (i.e., hexagon size) and, deciding what land class features are the fragmentation geometries.	High. The resistance layer values are entirely assigned based on expert opinion, so the resulting current map is a direct reflection of those decisions. Therefore, sensitivity analysis is required to understand how model predictions changes with different value assignments.	High. Assuming the existing U of T resistance layer(s) would be used, then the resistance layer values are entirely assigned based on expert opinion, so the resulting current map is a direct reflection of those decisions. Therefore, sensitivity analysis is required to understand how model predictions changes with different value assignments.	Moderate to High. Decision points include: defining which land cover class(es) to use for nodes; defining a minimum patch size; and, defining maximum dispersal distances to define link connections. If using a resistance layer to quantify functional connectivity, then the same sensitivities apply as for Circuit Theory and Least-cost approaches.
11. How computational expensive/demanding is the approach?	Moderate. Is dependent on study area size and number of patches in the calculations. Regional and larger projects often require areas to be tiled and results compiled together when processing is complete (e.g., Olson 2014).	High. Generation of the Alberta current density map required use of the Niagara supercomputer at the SciNet HPC Consortium in Ontario. Data needed to be re-scaled to permit computation by the supercomputer. Other broad-scale analyses have used tiling approaches and limited the resolution of the analysis (e.g., Pelletier et al. 2014; Bowman and Cordes 2015). Software is freely available.	Moderate to High. Dependent on study area size and resolution of resistance layer. Because broad-scale projects have used this approach (e.g., Anderson and Clark 2012), computational requirements are potentially manageable. Software to calculate resistant kernels is freely available.	Moderate. Dependent on study area size, number of patches, and number of links and approach to calculating links. Because many broad-scale projects have applied this approach, computational requirements seem manageable. Software to perform graph theory analysis is widely available.
12. How complex is it to utilize the approach to measure and monitor connectivity over time?	Moderate. The Alberta calculation required a tiling procedure and determination of an appropriate measurement scale that can capture change meaningfully. At the regional scale, measureable changes in the metric are unlikely. As well, the binary treatment of natural patches and barriers (i.e., fragmentation geometries), may not be able to reflect changes in certain types of land use.	High. Initial data processing has been completed and models have been explored, but map output products are not amenable to creating standardized comparisons over time since they do not provide a consistent and comparable metric, and computational requirements limit frequency at which analyses can be repeated. Predictive maps also require validation.	High. Resistance layer would need to be compiled and baseline predictive modelling performed and analyzed. Output maps can be compared over time to visualize spatial changes in connectivity and permeability; however, model predictions must be validated to know if connectivity has truly changed. Computational requirements may limit frequency at which analyses can be repeated	Moderate. The network model for the region would need to be defined (i.e., creating nodes and links), the data compiled, and the network analyzed. The network is edited at each future time step (e.g., add, remove or change nodes; update effective distance for links based on changes to the resistance layer), and metric(s) are recalculated. Difference or percent change in metric scores is calculated easily.

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Table 2 *continued*. Assessment of the four potential connectivity approaches and their potential to provide an indicator for use in the BMFs.

Evaluation Criteria	Effective Mesh Size	Circuit Theory Modelling	Least-cost Methods	Graph Theory/Network Analysis
13. How approachable, understandable, and communicable is the approach and its results to different stakeholders?	Medium. The general concept of effective mesh size is understandable in that as the measure gets smaller, it means that the landscape is more and more fragmented, but a clear understanding of what metric values are “good” or “acceptable” for a given landscape is lacking.	Medium. The current density map is appealing and allow for easy communication with stakeholders; however, confusion may occur as to what high and low values for current density mean or represent. The representation of the landscape as an electrical circuit may also be confusing or unintuitive to some.	Medium. Cumulative resistant kernel maps are appealing and allow for easy communication with stakeholders. The conceptual idea of moving across the landscape in locations of least resistance is also easy to understand and communicate. Density of dispersers might require some extra explanation for some users.	High. A network-level metric gives a bounded range of values for connectivity as a probability that can be easily interpreted. Network maps of nodes and links can also be used to easily communicate connectivity of the landscape visually.
14. How does the approach complement the Tier 1 indicator of amount of native or natural cover?	This metric measures the level of fragmentation of natural cover, so it assesses natural cover in a way that is different, but complementary to the Tier 1 indicator.	The approach attempts to assign a connectivity score to natural cover to characterize relative contribution of cover to connectivity; however, high current density values should not be assumed to be equivalent to high connectivity; therefore, areas of natural cover have the potential to be under- or over-valued by this indicator. There is the potential to conflict with the Tier 1 indicator in certain locations.	The approach can complement the Tier 1 indicator by showing where natural cover, landscape permeability, and predicted dispersal overlap. This allows for prioritization of areas for management or conservation; however, areas of low predicted disperser density should not be discounted as low value or areas of natural cover that are not important.	This approach complements the Tier 1 indicator by providing a measure of the functional connectivity of the network of natural cover patches. The network map provides a spatial and visual overview of where connected patches or clusters of patches exist and where there are missing links between patches. This may allow for prioritization of areas for management or conservation.
15. Are there opportunities to apply the approach or its outputs in other ways?	Yes. Mapped outputs can be used to show comparisons of metric values among regions or analytical units.	Yes. The map outputs can be used to visually assess where the probability of movement is the highest and to identify potential locations that are 'pinch points'. Resistance distance can provide an indication of patch-to-patch connectivity or isolation. This information can be used to prioritize locations for conservation and management action.	Yes. The map outputs can be used to visually assess where the most permeable areas are in the landscape, to locate potential corridor linkages, and to prioritize locations for conservation and management action.	Yes. Other network-, component-, and patch-level metrics can be quantified as part of the analysis to determine network properties such as, patch importance, link importance, and redundancy in the network. The network map can be used to visually assess where and why linkages are missing and to prioritize locations for conservation and management action.

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Table 2 *continued*. Assessment of the four potential connectivity approaches and their potential to provide an indicator for use in the BMFs.

Evaluation Criteria	Effective Mesh Size	Circuit Theory Modelling	Least-cost Methods	Graph Theory/Network Analysis
Overall Critique of Method	Effective mesh size has been applied in several regions internationally as an indicator of fragmentation, but its simplistic assumptions and focus on structural connectivity do not make it a meaningful measure of connectivity. It has been previously explored as an indicator in Alberta, and computational limitations and problems with interpretation prevented its practical use. It should not be used as a connectivity indicator in the BMF.	Circuit theory modelling provides a way to model connectivity across the landscape and can be extremely useful in locating pinch points and in prioritizing locations for conservation and management action; however, this approach is not recommended as a suitable way to quantify or measure connectivity, especially if the goal is to assess change over time. Its computational requirements provide an additional challenge in the context of monitoring and assessment; however, the interpatch resistance distance values that can be generated from a circuit theory analysis could be applied to a graph theory analysis.	Least-cost modelling is the most widely applied approach for predicting paths and corridors that provide the least resistance to movement for species, and it is widely applied as a planning tool for prioritizing locations for conservation and management action. The adapted mapped outputs of resistant kernel modelling could provide a measure of proportion of area that has high local connectivity, but it is not clear if this is an appropriate measure of connectivity to measure change over time given that it is a predictive model of connectivity. Validation and sensitivity analyses would be required before any conclusions could be made.	Graph theory has been applied widely to assess structural and functional connectivity, and to track change through time; thus, this approach provides the best option for creating a connectivity indicator that meets the majority of the BMF criteria. Some exploratory work would be required and decisions made on how to define the network elements (i.e., nodes and links), and how to measure distance for the links (i.e., Euclidean vs. resistance distance vs. effective distance), but existing data layers could be leveraged to facilitate the analytical process (e.g., use existing natural cover layers and resistance layers when developing the network elements).

Table 3. Simplified, comparative overview of the potential connectivity metrics associated with the methodological approaches evaluated in Table 2. The number(s) in brackets associated with each of the simplified evaluation criteria reference the corresponding criteria in Table 2.

Potential Connectivity Metric	**Evaluation Criteria**											
	Structural or Functional (1)	**Single Value** (2)	**Standardized Value** (3)	**Ability to Assess Change Over Time** (4, 5, 6, 7)	**Comparable Across Regions** (8)	**Data Requirements** (9)	**Reliance on Expert Opinion** (10)	**Computational Requirements** (11)	**Complexity to Implement and Use** (12)	**Communicability** (13)	**Complementary of Tier 1 Indicator** (14)	**Extensibility**** (15)
Landscape Pattern Metric												
Effective mesh size	Structural	Yes	No	Moderate	Yes	Low	Low to Moderate	Moderate	Moderate	Medium	Yes	Moderate
Circuit Theory Modelling												
Mean current density	Both*	Yes	No	Low	Yes	Moderate to High	High	High	High	Medium	Uncertain	Moderate
% cover "high" connectivity	Both*	Yes	Yes	Moderate	Yes	Moderate to High	High	High	High	High	Somewhat	Moderate
Least-cost Methods												
% cover "high" connectivity	Both*	Yes	Yes	Moderate	Yes	Moderate to High	High	Moderate to High	High	High	Somewhat	Moderate
Graph Theory/Network Analysis												
Integral Index of Connectivity	Structural	Yes	Yes	High	Yes	Moderate	Low to Moderate	Moderate	Moderate	High	Yes	High
Probability of Connectivity	Functional	Yes	Yes	High	Yes	High	Moderate	Moderate	Moderate	High	Yes	High
Equivalent Connected Area	Both*	Yes	Yes	High	Yes	Moderate to High	Moderate	Moderate	Moderate	High	Yes	High

*Depending on the input layers and methodological choices made during calculation, this metric may assess structural or functional connectivity.

**Extensibility refers to the approach's ability to provide additional data and/or measures or metrics that measure connectivity in different ways or at different scales.

5.0 Conclusions

The wide range of different approaches available to model and analyze connectivity can make it difficult to select a single approach, and it can be argued that there is no single "best" approach to assessing connectivity; instead, each approach is best suited to a different purpose. McClure et al. (2016) warn that connectivity approaches are too often selected based on popularity or ease of use. They instead urge that those considering connectivity analyses more critically and explicitly examine the links between model assumptions and outputs, and the goals or objectives the analysis is intended to fulfill. Choosing the right tool for the job is crucial in supporting policies and frameworks that are transparent and justifiable to stakeholders, and to ensuring that limited conservation resources are being meaningfully targeted towards management action and decisions that are the most likely to successfully support the maintenance of biodiversity into the future.

A functional network of connected natural habitat is essential to the long-term support of Alberta's diverse natural communities in response to human activity and development, as well as climate change. Thus, it is not surprising that there is a desire to include landscape connectivity as a Tier 2 indicator in the BMF as a way to complement the Tier 1 biodiversity indicator, and as a way to reflect regionally significant species and habitats of special concern. Despite the clear value of having a connectivity metric in regional BMFs, reliably measuring and quantifying connectivity is not an easy endeavour. This is because the approaches and tools that have been developed to assess connectivity are as varied as the goals and objectives that inspire an analysis of connectivity; consequently, each approach was designed with a specific purpose in mind, and as a result, not all approaches to assessing connectivity are well suited to address the management question(s) that inspired the analysis.

This report has presented four potential approaches that could be adopted to assess connectivity at the regional scale, and each of these approaches and the associated metrics that could be used to assess regional connectivity in Alberta have been described, explained, and critiqued with regards to their ability to successfully function as an indicator both practically and meaningfully within BMFs. Importantly, it should be apparent from this review that connectivity analyses are either generally focused on mapping and predicting, or measuring and assessing, and that for an approach to be an effective indicator, it should be developed with measurement and assessment in mind. When selecting a connectivity indicator for use in the BMFs, two of the most important criteria are the ability of the method and associated metric to effectively assess connectivity at a single point in time, and to be able to meaningfully track changes in connectivity over time. Given these requirements, we consider graph theory to be the most suitable approach for quantifying change in regional habitat connectivity as part of the BMF.

Notably, graph theory offers several viable options for a network-level metric (i.e., a composite, regional-level measure) that could be adopted as a connectivity indicator in Alberta, including: integral index of connectivity (IIC), the probability of connectivity index (PC), and the equivalent connected index (EC or ECA), and each of these metrics has its own particular benefits and strengths that must be carefully considered when selecting a connectivity metric for Alberta. Thus, as a critical next step, these metrics should be more fully interrogated to determine which one best aligns with the metric criteria that are considered the most important from a regional management perspective. For example, if a structural connectivity approach is preferred over a functional connectivity approach, then the IIC would be the most appropriate regional connectivity metric; however, if there is a preference to use a metric that incorporates more functional aspects of connectivity, such as effective or resistance distance between patches or patch quality, then PC would be a better option for use as a regional indicator. Alternatively, if there is a strong preference to communicate the changes in connectivity over time in area units, as opposed to using an index that ranges from 0 to 1, then EC would best meet regional planning needs.

Given that there are several options moving forward with respect to adopting and applying graph theory as an approach for assessing regional connectivity, the next step is for the BMF STC and other key individuals to articulate which criteria and traits are the most relevant and important for a connectivity indicator in Alberta. This will require careful consideration of the challenges and benefits of adopting each metric, and ultimately, deciding which metric will provide a strong, reliable, and meaningful assessment of connectivity as part of the BMF.

5.1. Closure

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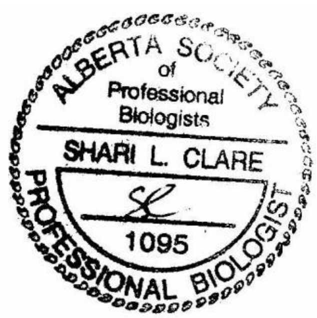

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Appendix 2: Summary of Cost Distance Analysis

Following the approach from section 2.4.2, Figures A1 and A2 show average cost distances for Grass-Shrub, Upland Forest, and Lowland Forest under the reference conditions and in 2021, respectively, while Figure A3 shows percent changes of average cost distances for the three habitat types between 2021 and reference conditions.

For each of the three habitat types analyzed, we found that the 2021 average cost distances increased from those under the reference condition (Figure A3). This is because on average, we have weighted anthropogenic disturbances as higher barriers to dispersal than competing native habitat types (e.g., dispersal of Grass-Shrub through Lowland Forest). The average cost distance increased on average by 29% (sd = 33%, max = 126%) for Grass-Shrub, 49% (sd = 55%, max = 239%) for Upland Forest and 63% (sd = 68%, max = 272%) for Lowland Forest.

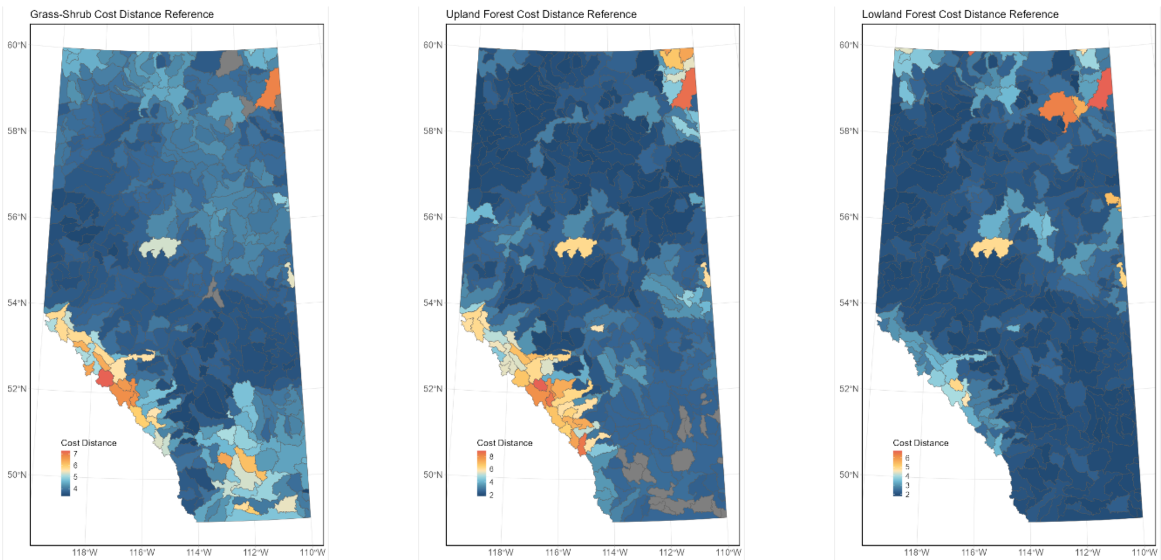

Figure A1. Average cost distances for Grass-Shrub (left), Upland Forest (centre), and Lowland Forest (right) under the reference conditions. Cost values are calculated using 10 m pixels and aggregated for each HUC-8 watershed.

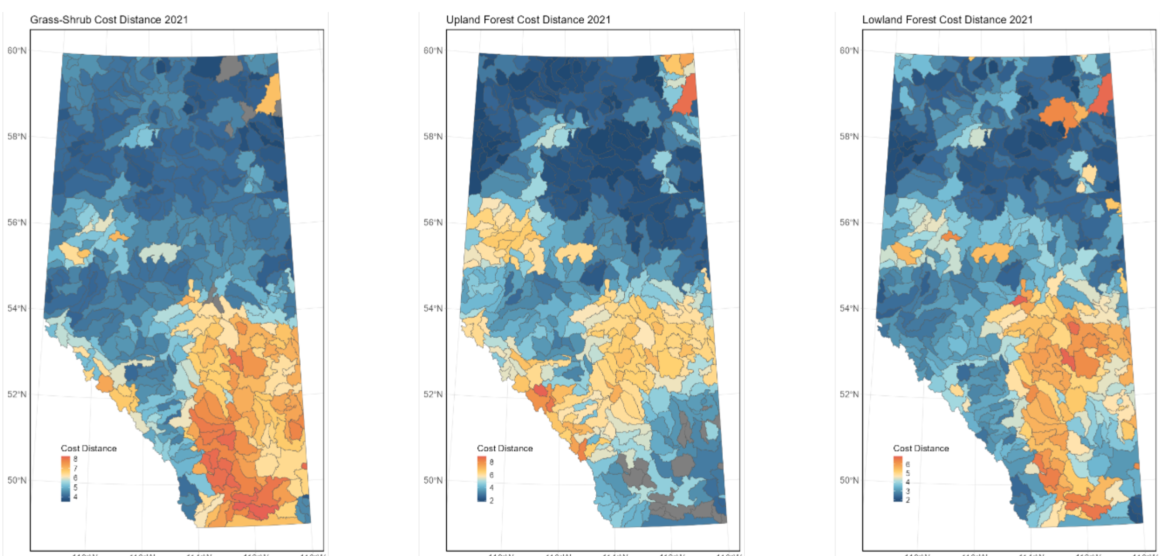

Figure A2. Average cost distances for Grass-Shrub (left), Upland Forest (centre), and Lowland Forest (right) in 2021. Cost values are calculated using 10 m pixels and aggregated for each HUC-8 watershed and for each analysis year.

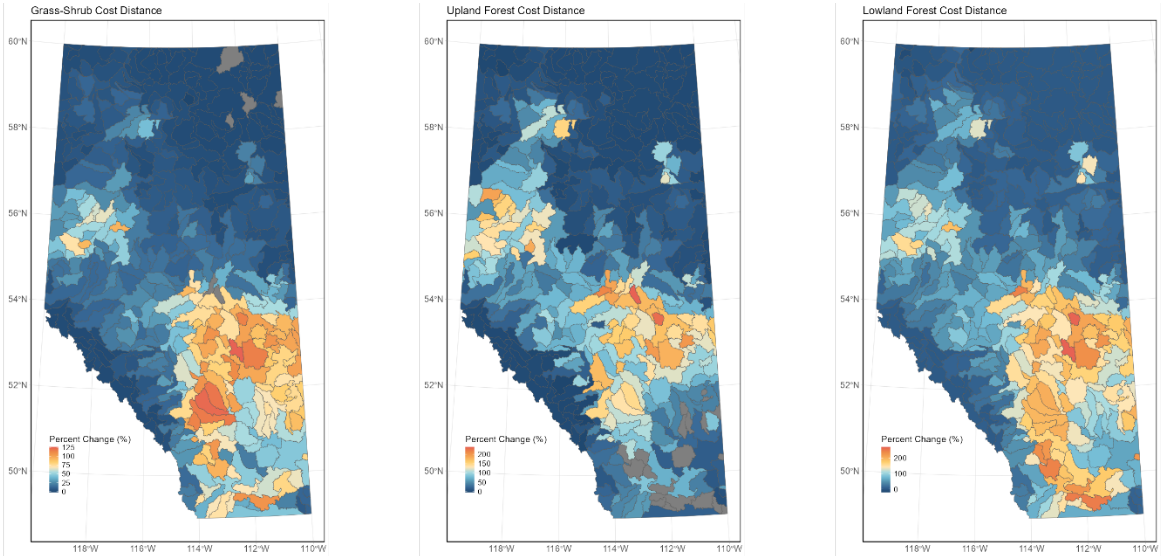

Figure A3. Percent changes of average cost distances for Grass-Shrub (left), Upland Forest (centre), and Lowland Forest (right) between 2021 and reference conditions.