Landscape Connectivity and Movement Corridors for Grizzly Bears in the Yellowhead Ecosystem, Alberta: A Preliminary Assessment

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1.0 INTRODUCTION

Maintaining habitat connections for movement across fragmented landscapes is important for the long-term conservation of grizzly bear populations. Grizzly bears range across multiple jurisdictions and therefore an integrated management approach is necessary to ensure their long-term persistence (NESERC 2000). As a result, the focus of this analysis is on applying graph theoretic methods in conjunction with RS, GIS and GPS data to study and quantify landscape connectivity associated with female grizzly bears within the Yellowhead Ecosystem, Alberta.

Landscape connectivity refers to the functional linkage among habitat patches, either because habitats are physically adjacent or because the dispersal range of the species effectively connects patches across the landscape (With et al. 1997). Therefore, whether or not a landscape is considered connected depends upon the species ability to utilize and move through elements of the landscape. This is largely the case with grizzly bears, as they require connections for movement on a daily to seasonal basis within their home ranges (Noss et al. 1996).

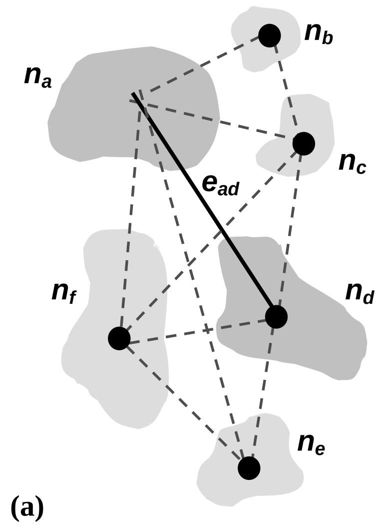
Graph theory is a heuristic approach allowing researchers to examine connectivity in an ecological context with specific emphasis on species movement and landscape interactions. The approach utilizes the basic elements of nodes (centroids of habitat patches), edges (connections between patches) and paths (connections between numerous patches). Schwab et al. (in review) have previously developed, applied and validated the graph theoretic models combined within GIS to explore habitat connectivity in relation to female grizzly bear movement within individual home ranges. This report addresses the effort to apply, quantify and validate the graph theory approach for female grizzly bears at the landscape level. The landscape model was developed using GPS data collected in 1999 and 2000 and validated with 2001 and 2002 GPS data for female grizzly bears across the FMFGBRP study area.

2.0 METHODOLOGY

The authors adopted and modified the graph theoretic approach for specific application to female grizzly bears within the FMFGBRP. Spatial data analysis was conducted using C and FORTRAN modules linked within ArcInfo to create least-cost path graph edges and calculate connectivity measures. ArcInfo provided a working environment capable of performing both vector and raster/grid analysis.

Major data inputs required for the modeling effort include Resource Selection Function (RSF) defined habitat patches (basis for nodes), GIS grid-based landscapes (basis for least-cost path creation), and GPS bear movement data for model validation. Figure 1a represents a basic landscape graph structure comprised of straight line connections. In Figure 1b, edge e_{ad} and edge e_{de} (represented by the solid line) are created using least-cost path (LCP) modeling in effort to generate functional connections (edges) between habitat patches (nodes) specific to grizzly bear movement.

Figure 1 - (a) Basic landscape graph structure showing key patches identified by nodes (n) with edge $e_{ad}=n_a n_d$ connecting patches n_a and n_d; (b) example of least-cost path edges e_{ad} and e_{de} connecting patches n_a to n_d and n_d to n_e based on cost surface modeling.



Additional efforts are underway to improve computational and data limitations associated with the modeling procedure and graph code. The following methodological approach focuses on 1) graph generation and distance threshold definition, 2) graph analyses (simple and advanced descriptors), and 3) graph validation with simple habitat interactions.

2.1 Graph Generation and Distance Threshold Definition

The graph theory approach was applied to generate a landscape-level graph for the extended FMFGBRP study area (spatially limited by the extent of the RSF model). For this analysis, nodes were derived from a resource selection function (RSF) model representing habitat patches with the relative probability of occurrence for females grizzly bears > +1.5 SD from the mean probability of occurrence created by Scott Nielsen, University of Alberta. Each node represents the center of the identified RSF habitat patch and contains attribute data regarding patch characteristics to be used later in graph analyses. RSF patches smaller than 5.0 hectares were not selected as nodes but were maintained in graph analysis as suitable low-cost habitat within the cost surface used for edge creation.

Cost surfaces were developed at the annual level for initial performance comparison. To test the utility of cost surfaces as surrogates for modeling female grizzly bear movement, four different permeability surfaces were evaluated using Least-Cost Path (LCP) modeling (Walker and Craighead 1997, Purves and Doering 1999). Cost surfaces were validated based on comparisons in distance (m) between the LCP generated and withheld interim GPS location data for 2001 females. Statistical comparison of mean distances for each cost surface model was accomplished with a single factor analysis of variance (ANOVA). See Schwab et al. (in review) for specific details and further explanation regarding cost surface development and validation. The RSF cost surface model which performed best in model validation (based on consistent lowest mean distance) was used to further define 'edges' or connections between habitat patches within the graph generation procedure.

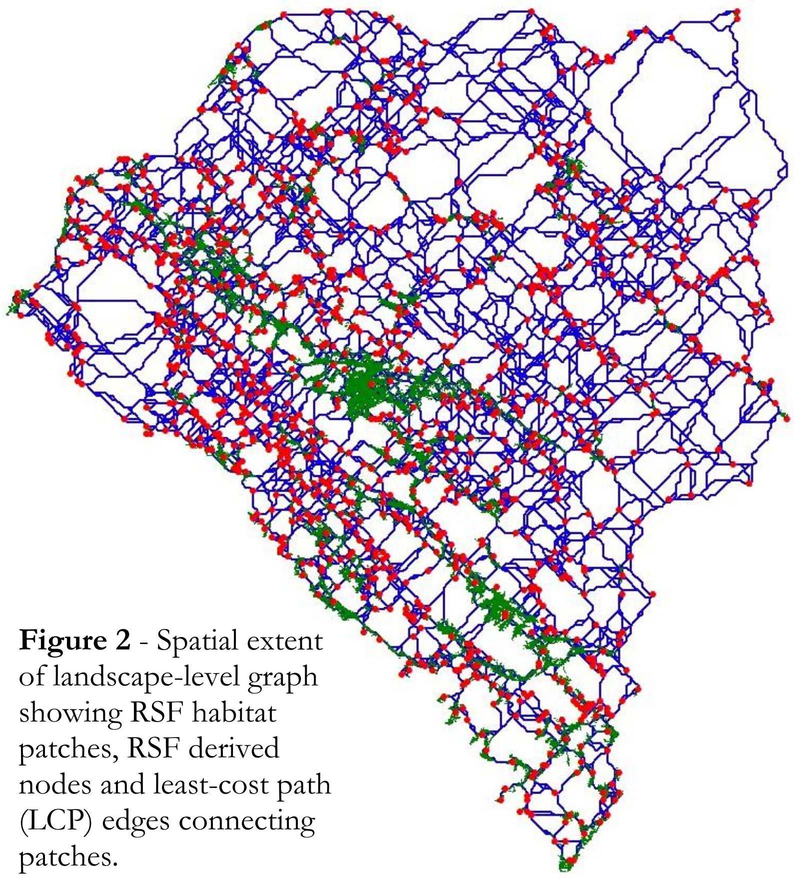


Figure 2 - Spatial extent of landscape-level graph showing RSF habitat patches, RSF derived nodes and least-cost path (LCP) edges connecting patches.

Using the RSF cost surface, resampled to 500 meters, least-cost path connections or edges were generated to represent all possible connections between nodes (See Figure 2). The basic landscape-level graph has 1,176 nodes representing RSF patches and 1,407,760 edges representing potential landscape connections between patches. Each LCP edge approximates the actual landscape distance traversed by a female grizzly bear as it moves from one patch to the next in a heterogeneous landscape. The landscape graph drawn in Figure 2 is 'connected', as such each node is connected to every other node.

Edges within the graph structure are further defined by distance. For example, what minimum or maximum distance is required to maintain connections between patches or nodes? Distance statistics based on GPS location data were calculated for 13 female grizzly bears (6 females for 1999 and 11 females for 2000) over a two year period (Table 1). Between point distances (m) were examined using percentiles, quartiles, minimum, maximum, mean and daily movement rate (total distance / number of sample days). Overall combined averages were used to examine graph response and simple connectivity measures at the landscape-level. Advanced graph descriptors were calculated using the mean, daily movement rate and 95^{th} percentile distance thresholds.

Table 1 – Between point distance statistics (distance thresholds) based on 2001 and 2002 female GPS location data showing averages by year.

Quartiles / Stats	2001 Averages (meters)	2002 Averages (meters)
Minimum	11.307	4.296
Percentiles 5%	57.960	22.204
Percentiles 10%	90.526	45.976
Percentiles 20%	169.431	130.420
Percentiles 25%	225.576	185.084
Percentiles 30%	331.618	256.563
Percentiles 40%	576.175	433.826
Percentiles 50%	868.381	738.398
Percentiles 60%	1238.749	1186.919
Mean	**1497.140**	**1740.158**
Percentiles 70%	1722.995	2005.101
Percentiles 75%	2120.273	2512.166
Percentiles 80%	2426.174	3058.129
Percentiles 90%	3657.154	4742.056
Daily Movement Rate	**5257.587**	**6787.880**
Percentiles 95%	**5693.450**	**4533.076**
Maximum	16891.810	15398.488

2.2 Graph Analyses

Once the landscape graph is generated (Figure 2), simple and advance graph connectivity descriptors are further explored based on the previously defined dispersal thresholds. Simple graph connectivity descriptors include the resulting number of nodes and LCP edges required to define the graph structure in addition to the corresponding gamma and beta measures (Table 2). Total LCP edge length is further compared to straight-line edge length between each set of nodes to establish the ratio or sinuosity of each edge. By measuring the difference between straight-line length and least-cost path or actual length, the ratio or degree of topological complexity of each linear feature in the graph structure can be analyzed. Additional simple graph descriptors include, between patch average distance (meters), total graph area based on habitat patches (nodes), and visual changes to graph structure based on the distance threshold employed.

Advanced graph connectivity descriptors were completed using FORTRAN modules created to evaluate the importance of individual elements (edges and nodes) to the entire graph structure. Each module was run using the mean, 95^{th} percentile and daily distance thresholds for further comparison of results. More specifically, advanced graph connectivity descriptors include programs

EDGES, SENSINODE, PATHS, THINEDGE, MINNODE and ENDNODE. Program EDGES analyzes the graph structure with specific focus on edge components while creating probability and adjacency matrices dependant upon the distance threshold employed. Program SENSINODE evaluates the landscapes reproductive potential, establishes graph diameter and measures the sensitivity to each node or habitat patch to the overall graph structure. Program PATHS simply defines the graph structure as connected or not connected; while THINEDGE evaluates connectivity response to 100 meter iterative edge distance change. Programs MINNODE and ENDNODE explore node sensitivities to iterative removal based on patch size and patch location. Overall, advanced connectivity results are also explored visually to further understand geographic components (habitat patches and corridors) of importance.

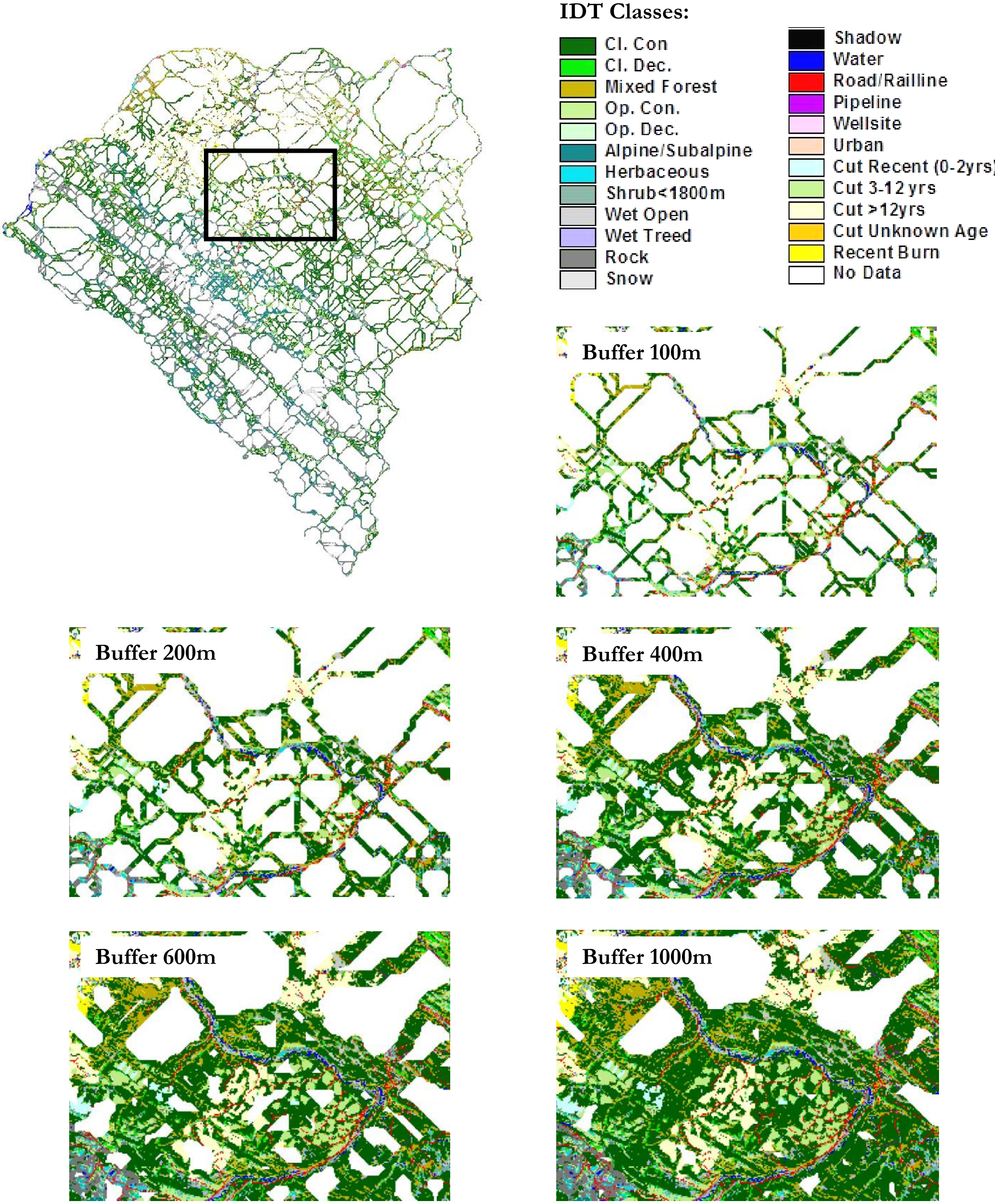
2.3 Graph Validation with Simple Habitat Interactions

Graph validation was completed using 2001 (14 individual females) and 2002 (15 individual females) GPS location data. Females used in graph validation were further segmented into two groups 1) individual females previously included in 1999/2000 model development, and 2) individual females not previously used in 1999/2000 model development. Landscape graph validation was further conducted by calculating the Euclidean or straight-line distance (m) of each female GPS location point to the closest LCP edge using GIS techniques. More specifically, the complete landscape graph structure (Figure 2) was used to generate a 100 meter distance grid surface representing distances from each least-cost path edge or connection outward across the landscape study area. Distances (m) for each female 2001 and 2002 GPS location point to the nearest LCP edge were extracted by intersecting the validation point surface with the distance grid. Results were further classified into 100, 200, 400, 600 and 1000 buffer intervals for simple frequency analysis.

Simple habitat interactions were also explored for landscape level connections using edge buffers at 100, 200, 400, 600 and 1000 meter distances. IDT habitat composition (class) and amount (m^2) were analyzed for each buffer interval (see Figure 3 below). This approach was intended to generally explore the types of habitat occurring within proximity to landscape edge connections. Furthermore, it may potentially be assumed that these habitats are also used by female grizzly bears for movement between identified RSF patches.

Figure 3 - Landscape graph with path buffers showing detailed IDT habitat interactions for 100m, 200m, 400m, 600m, and 1000m.

3.0 RESULTS


IDT Classes:
Cl. Con
Cl. Dec.
Mixed Forest
Op. Con.
Op. Dec.
Alpine/Subalpine
Herbaceous
Shrub<1800m
Wet Open
Wet Treed
Rock
Snow
Shadow
Water
Road/Railline
Pipeline
Wellsite
Urban
Cut Recent (0-2yrs)
Cut 3-12 yrs
Cut >12yrs
Cut Unknown Age
Recent Burn
No Data
Buffer 100m
Buffer 200m
Buffer 400m
Buffer 600m
Buffer 1000m

3.1 Simple Landscape Graph Descriptors

Analysis was conducted at the landscape scale to assess connectivity for the female grizzly bear population in the FMFGBRP study area. The graph structure had a total patch area (reproductive potential) of 56,790.60 hectares with a mean between patch distance of 57.910 kilometers. Mean graph sinuosity or topological complexity was 1.3770 indicating greater convolution or variability of line connections when compared to individual results (Schwab 2003). Distance thresholds (average between point distance in meters) were employed to limit graph edge connections and further explore resulting connectivity measures quantitatively and visually.

Reduction in the average distance threshold employed resulted in limited number of edge connections and decreased gamma (γ) and beta (β) indices (Table 2). Simple connectivity results further indicated that connectivity was predominantly restricted unless the maximum distance threshold or no distance threshold was employed. Regardless of the distance threshold employed, connectivity results quantitatively indicated the landscape structure to be poorly connected and inversely, highly fragmented.

Table 2 - Connectivity response to changes in average distance rate employed

Quartiles / Stats	Average Distance (meters)	# of Edges	# of Nodes	Gamma (γ)	Beta (β)
Minimum	**6.771**	0	1176	0.000	0
Percentiles 5%	**34.824**	0	1176	0.000	0
Percentiles 10%	**61.699**	0	1176	0.000	0
Percentiles 20%	**144.189**	0	1176	0.000	0
Percentiles 25%	**199.375**	0	1176	0.000	0
Percentiles 30%	**283.053**	0	1176	0.000	0
Percentiles 40%	**484.067**	0	1176	0.000	0
Percentiles 50%	**784.274**	760	1176	0.001	0.646258503
Percentiles 60%	**1205.212**	954	1176	0.001	0.81122449
Mean	**1654.387**	2053	1176	0.003	1.745748299
Percentiles 70%	**1905.534**	2530	1176	0.004	2.151360544
Percentiles 75%	**2373.851**	3809	1176	0.006	3.238945578
Percentiles 80%	**2835.086**	5539	1176	0.008	4.710034014
Percentiles 90%	**4359.149**	11408	1176	0.017	9.700680272
Daily Rate	**4942.620**	13582	1176	0.020	11.54931973
Percentiles 95%	**6247.777**	20577	1176	0.030	17.49744898
Maximum	**15925.543**	99125	1176	0.143	84.28996599
Total Possible		**1407760**	**1176**	**2**	**1176**

Overall landscape connectivity as represented by gamma (γ) was substantially lower than habitat connectivity levels demonstrated by individual females (Schwab et al. in review). Figure 5 illustrates the influence of changing functional edge distance on the resulting landscape structure. Graph edges or connections were defined by mean, 95th percentile, daily movement and maximum distance thresholds (Table 2). As the distance threshold increased, the graph structure became more 'connected' and exhibited a higher gamma value (Figure 5d). Conversely, as the distance threshold decreased the graph structure became 'less connected' with an appearance of sub graphs and reduced gamma values (Figure 5a). The landscape graph structure distinctly disconnected somewhere between a 6.2 km and 16 km functional edge distance. This critical threshold will further be identified by the THINEDGE procedure. The current configuration of the landscape is connected for species with a movement range of at least 16 km. For species with a movement range under 16 km, the landscape is naturally fragmented with travel between subgraphs difficult and unlikely.

Figure 4 demonstrates extremely high levels of fragmentation or lack of connectivity. This was a direct function of distance and while nodes within close proximity to one another were connected, nodes substantial distances apart were not. This was further illustrated by the small band of connections running northwest – southeast in the southwest portion of the landscape graph (Figure 5a). Low overall gamma (γ) results seen across all distances at the landscape level indicated that quantitatively, the FMFGBRP study area was not considered connected. Furthermore, the visual interpretation demonstrated fragmentation occurring first in the northeast corner of the study area. This coincides with increased human disturbance such as road structures and decreased large, contiguous habitat patches. Combining the simple connectivity descriptors with the advanced descriptors will further identify which connections and habitat patches are most important to the overall maintenance of landscape connectivity.

Figure 4 - Connectivity demonstrated by gamma (γ) calculated for both individual females (home range connections) and population females (landscape-level connections) for comparison.

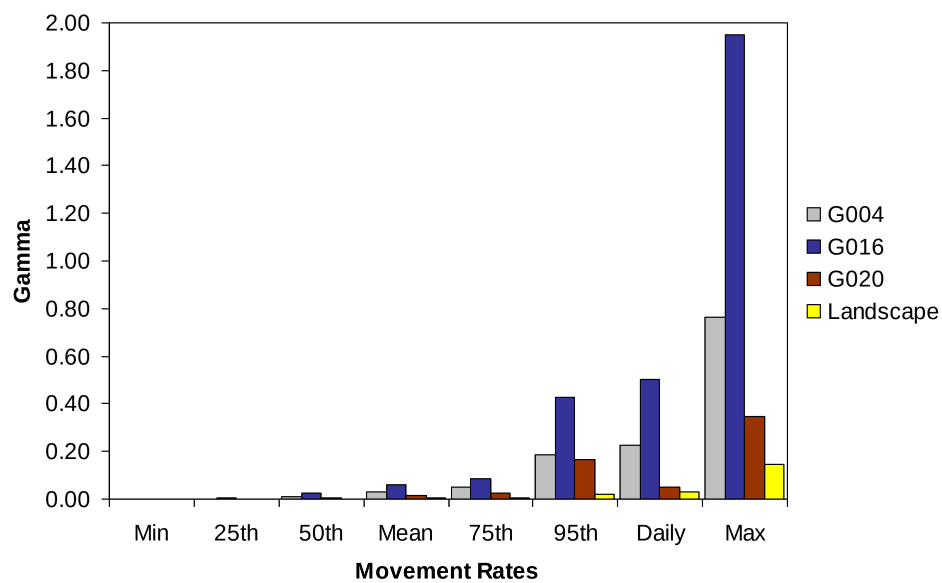
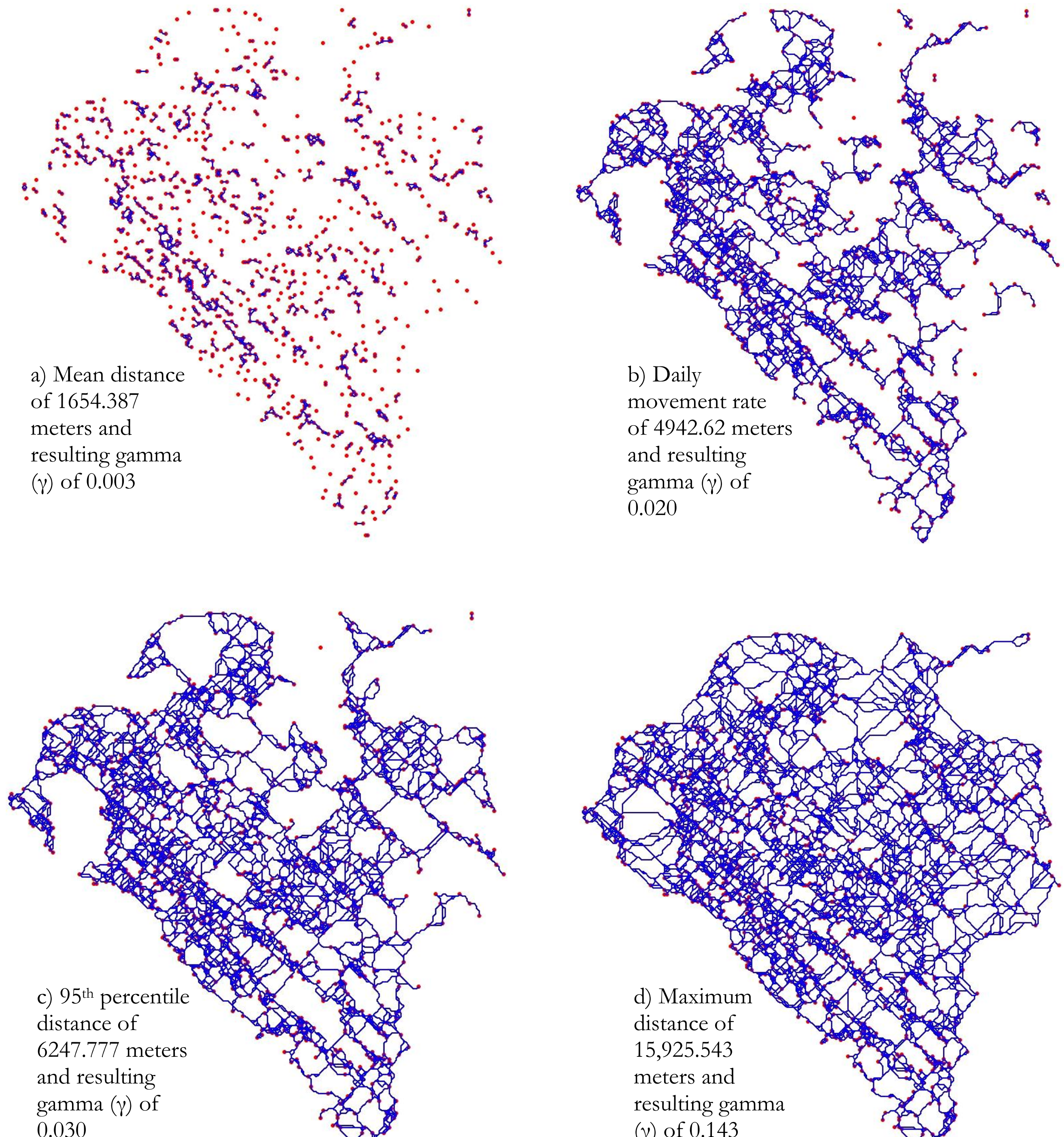


Figure 5 - Demonstrating changes to graph structure and connectivity resulting from changes to movement rate employed.


a) Mean distance of 1654.387 meters and resulting gamma (γ) of 0.003
b) Daily movement rate of 4942.62 meters and resulting gamma (γ) of 0.020
c) 95th percentile distance of 6247.777 meters and resulting gamma (γ) of 0.030
d) Maximum distance of 15,925.543 meters and resulting gamma (γ) of 0.143

3.2 Advanced Landscape Graph Descriptors

Results generated at the landscape level were calculated using distance thresholds or movement rates employed for simple connectivity analysis. These include: mean at 1654.39 meters, 95^{th} percentile at 6247.78 meters, and daily movement rate at 4942.62 meters (Table 2). The landscape graph upon input was defined as unconnected for all distance thresholds. The mean distance threshold was significantly less connected demonstrated by an increase to the number of graph components or subgraphs with a low resulting largest graph diameter of almost 50 kilometers (Table 3). The 95^{th} percentile distance threshold demonstrated the lowest levels of fragmentation with 3 main graph components occurring across the landscape.

These results were largely influenced by the distance threshold employed. At the landscape level, connectivity may be better analyzed using species dispersal distance or male grizzly bear distance / movement rates. Furthermore, male grizzlies are most likely to use long distance connections or corridors for travel to females (Craighhead and Vyse 1996). However, as the colonization of empty habitat patches often depends on female movement over shorter distances, connections are required at the landscape level that further support females and their offspring (Craighead and Vyse 1996). In addition, grizzly bear dispersal has not been well documented and often subadults will establish home ranges encompassing a portion of their mother's original home range (Weaver et al. 1996). As such, although this research focuses on defining distance based on females distance statistics, it is important to note that other options exist when defining these parameters.

Table 3 - Program EDGE output showing resulting graph components based on distance threshold employed

	Distance Threshold	Connected / Unconnected	# of Graph Components	# of Edges in Largest Component	Resulting Graph Diameter (meters)
Landscape	Mean	Unconnected	328	451	49819.91
	95th	Unconnected	3	10234	80997.48
	Daily	Unconnected	6	6695	848825.91

Probability and adjacency graphs generated at the landscape level demonstrate edges or connections which are adjacent and represent high probabilities with thicker dark blue lines. Figure 6 and Figure 7 demonstrate greater numbers of desired connections at the 95^{th} percentile distance threshold. While the mean distance threshold produced lower numbers of adjacent edges with decreased probabilities, enough high probability and adjacent connections remained to provide major travel corridors across the landscape for female grizzly bear populations. However, in order to remain conservative, land use managers should focus on maintaining at least the mean distance probability connections for travel between patches (Figure 6).

Figure 6 - Landscape graph structures showing nodes and edge connections based on probability and further defined by mean, 95^{th} and daily distance thresholds.

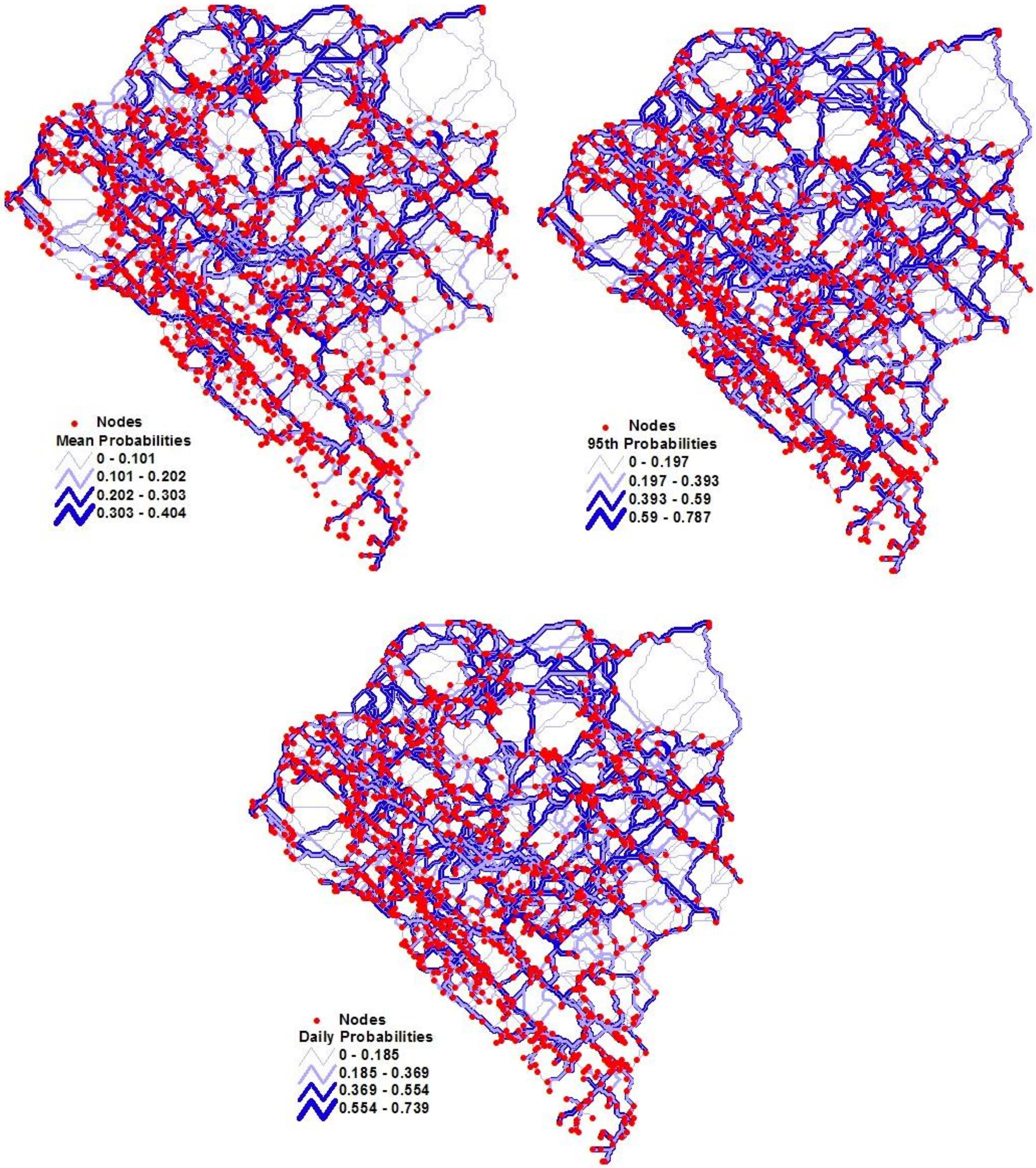
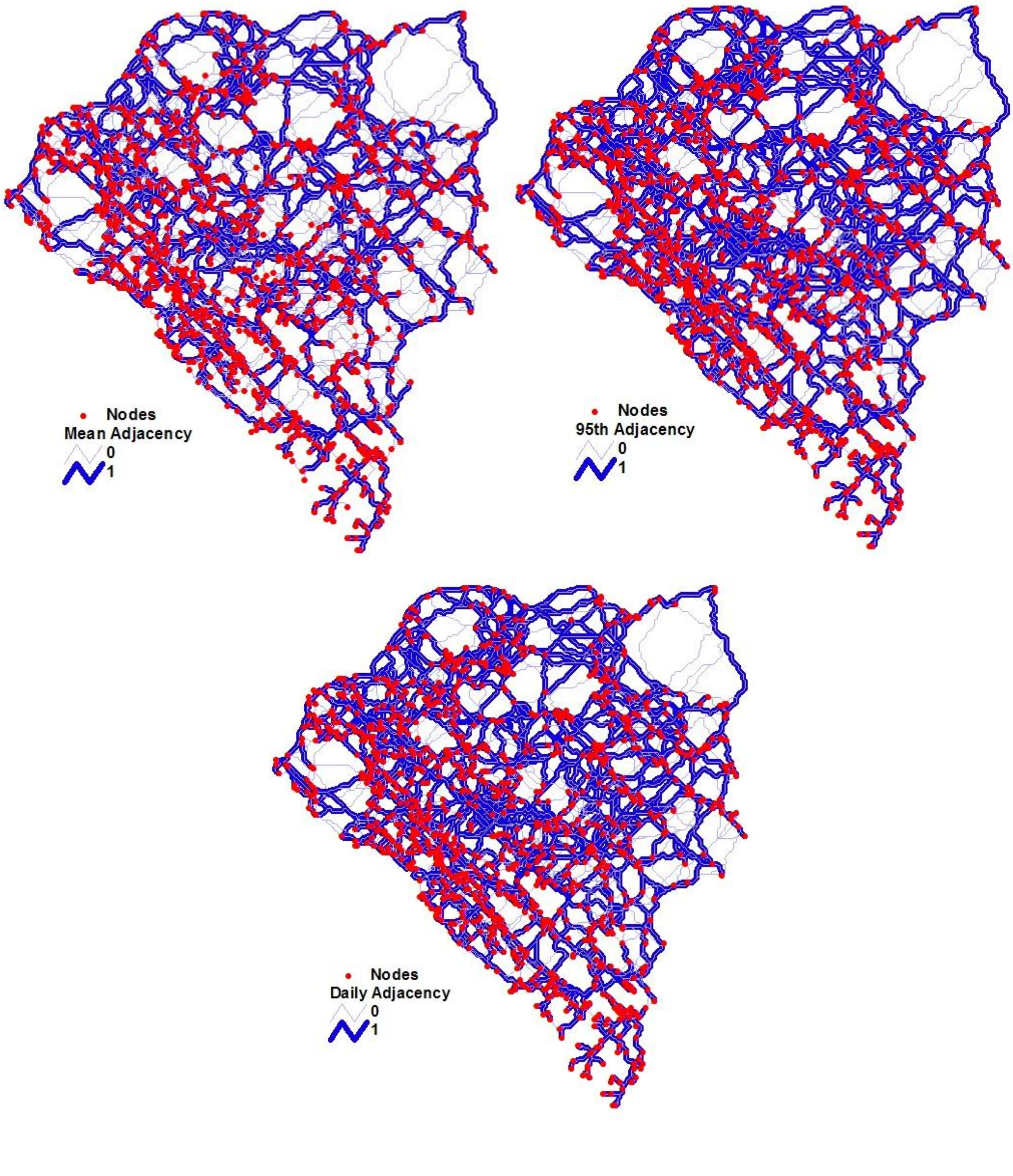


Figure 7 - Landscape graph structures showing nodes and edge connections based on adjacency and further defined by mean, 95th and daily distance thresholds.



Iterative edge removal results demonstrate the landscape graph beginning to disconnect and fragment into subgraphs at approximately a 5 km edge distance (Figure 8). Below a 3 km edge distance, the graph quickly segmented into numerous graph components or subgraphs, each containing only a few nodes. Graph diameter increased quickly with incremental distance, peaking first at 3 kilometers and again at 4.5 kilometers. Beyond 5 kilometers however, graph diameter began to slowly level out.

The distinct edge or critical threshold was identified at approximately 2.5 kilometers. This trend was a direct result of the basic landscape structure. As no bear-related distance thresholds were employed, all edge and node connections were simply defined by original habitat placement. Furthermore, these results indicated the natural configuration of the landscape to be unconnected at small distances. For female grizzly bears, distances of 2 and 3 kilometers are easily traversed. However, human-related mortality, not included in this analysis, may occur within the identified edge threshold range.

Figure 8 - Landscape THINEDGE results with no distance threshold employed and completed using 100 meter increments from 0 to 15000.

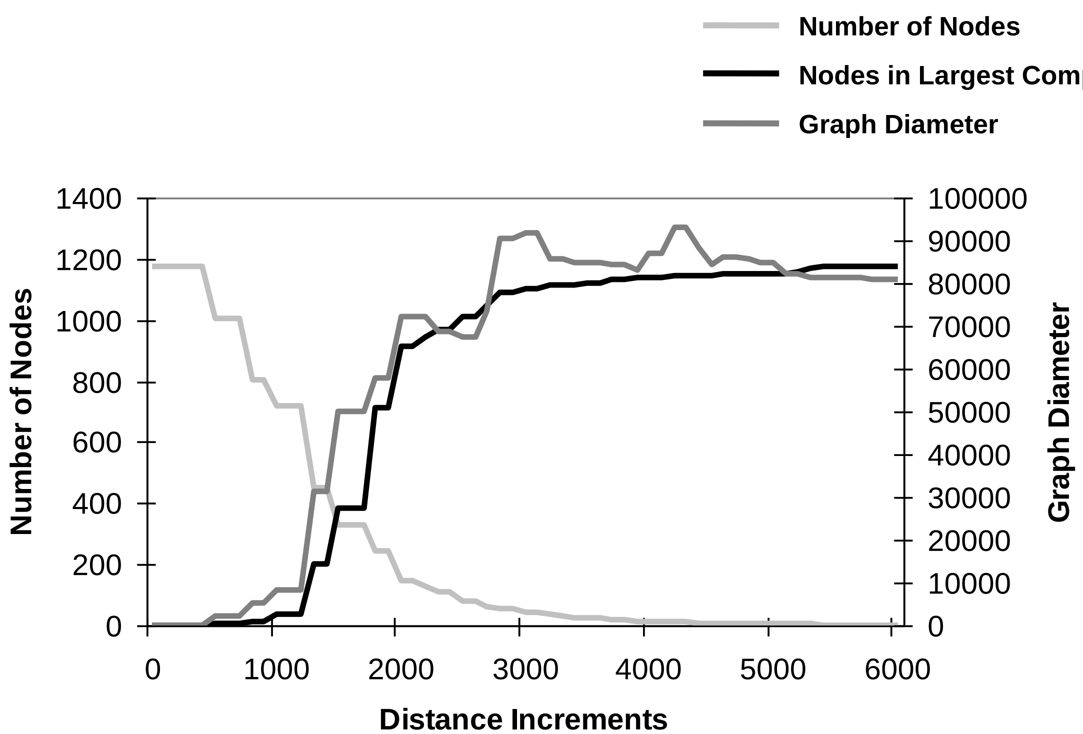
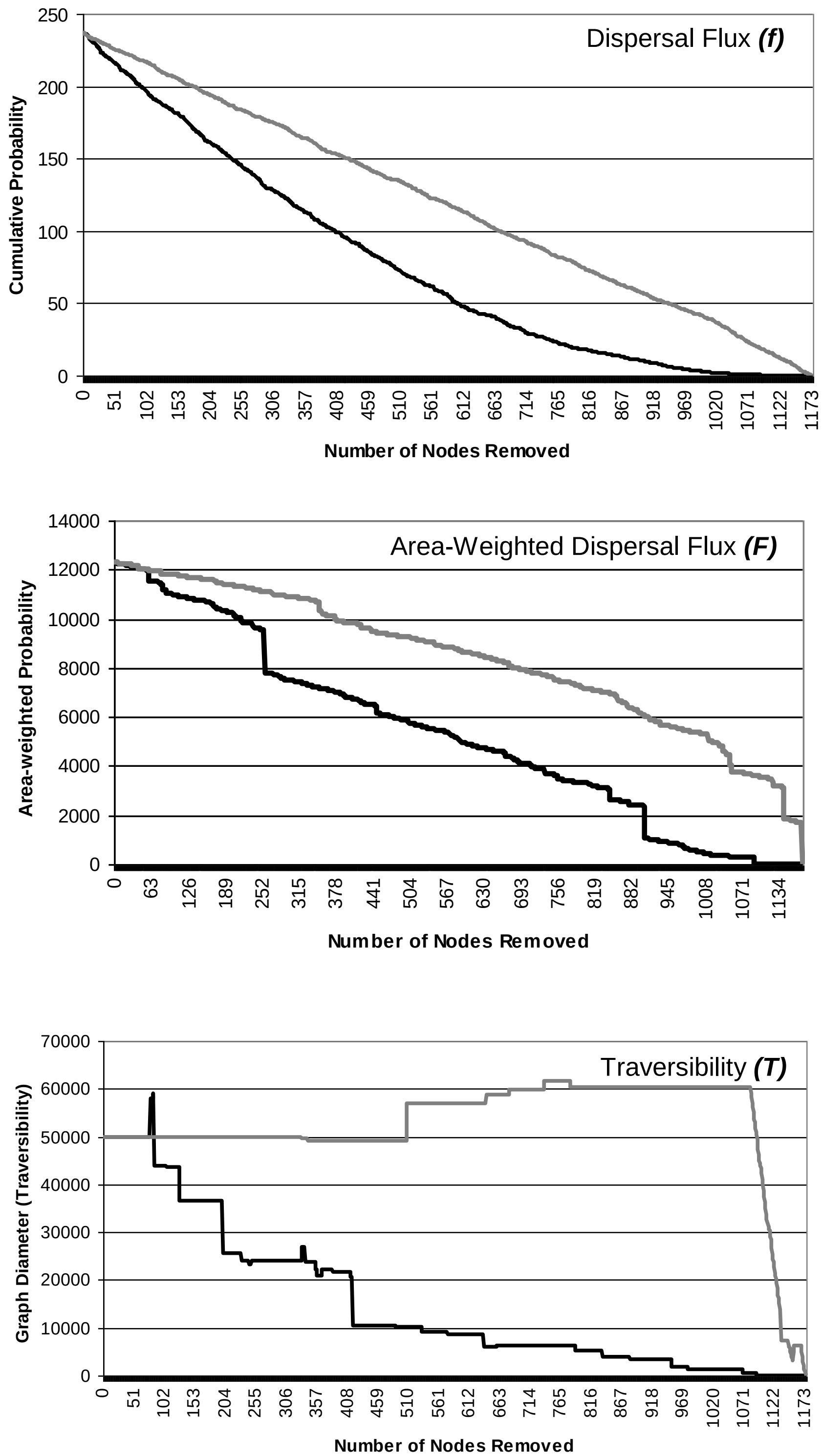
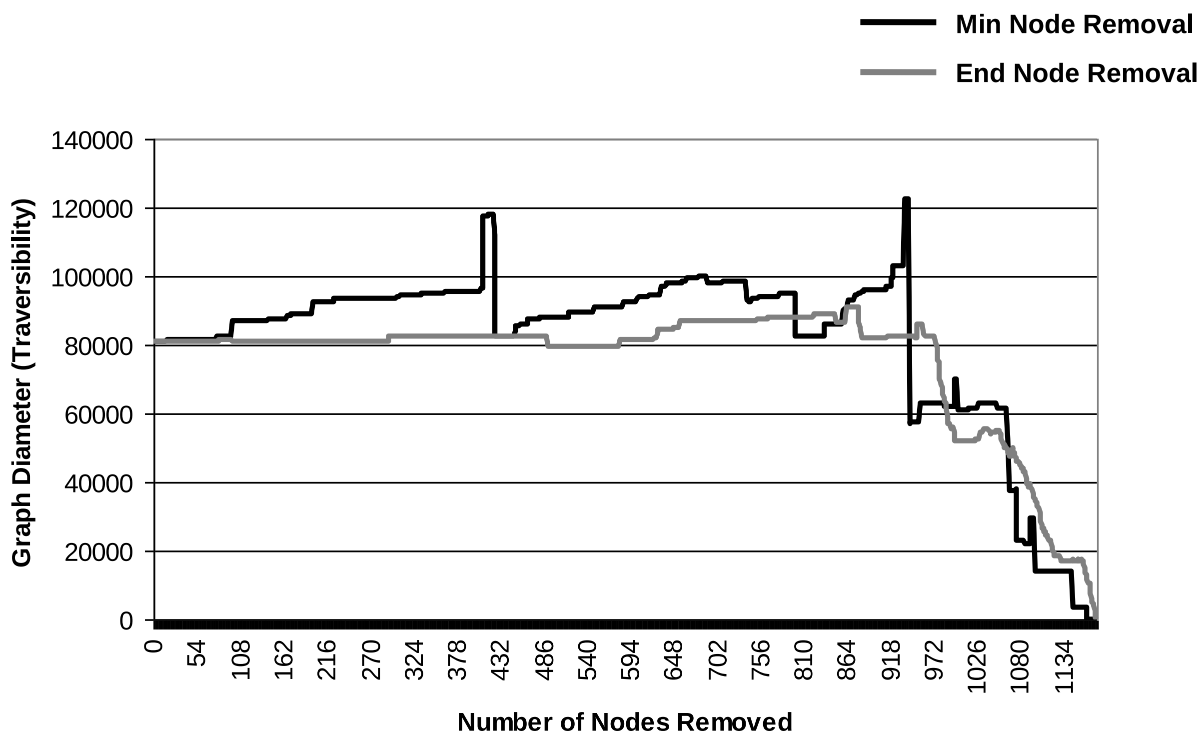


Figure 9 - Landscape MINNODE and ENDNODE results showing comparisons based on both minimum and end node removal defined by mean distance threshold.



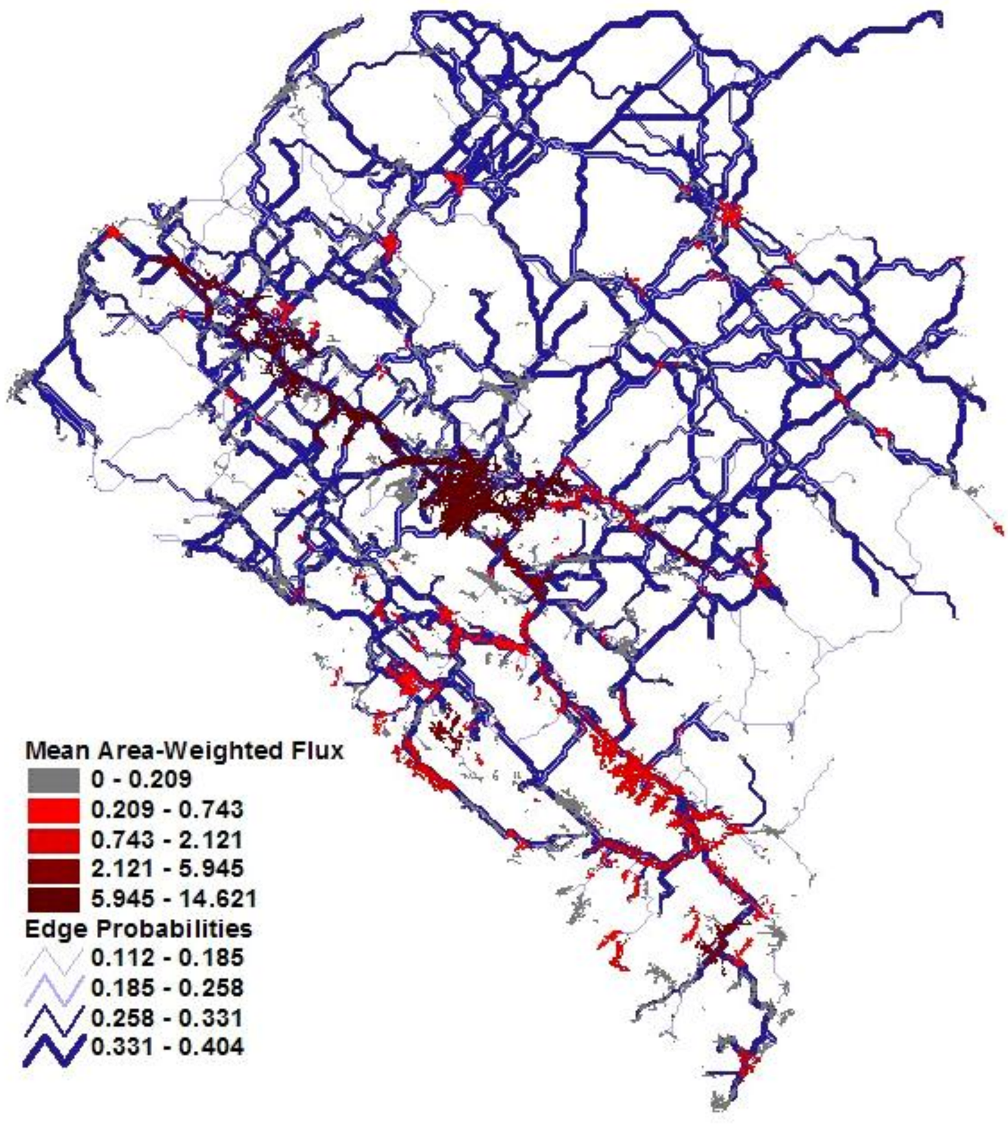
MINNODE and ENDNODE results were similar at 95th percentile and daily distance thresholds for dispersal flux ***(f)*** and area-weighted dispersal flux ***(F)***. Results differ in that ENDNODE flux values were quite higher than those indicated with MINNODE. In addition, ENDNODE graph traversibility was maintained longer falling off abruptly when approximately 80 percent of nodes were removed from the graph structure. Results indicated the majority of graph nodes, which provide the basis for graph diameter, exist within the interior of the graph structure. MINNODE graph traversibility was affected gradually as nodes were removed demonstrated by the stepping results in Figure 9. Differences do occur for traversibility ***(T)*** at increased distance thresholds as demonstrated by Figure 10. At the 95th percentile distance threshold there appeared to be little difference between MINNODE and ENDNODE removal procedures to overall graph traversibility ***(T)***. However, MINNODE results illustrated larger variation in response as nodes were removed from the structure. For grizzly bears, MINNODE and ENDNODE results allow land use managers to envision the quantity of habitat loss acceptable to grizzly bear populations based on graph structure.

Figure 10 - Landscape MINNODE and ENDNODE traversibility results showing comparisons based on both minimum and end node removal defined by 95th percentile distance threshold.



Node sensitivity results using program SENSINODE tested each landscape patch within the graph structure. The sensitivity of each landscape patch was assessed using recruitment ***(R)***, dispersal flux ***(f)***, area-weighted dispersal flux ***(F)***, and traversibility ***(T)*** metrics. The resulting spatial arrangement of patches indicating sensitivity to area-weighted dispersal flux ***(F)*** provide for interesting interpretation. As area-weighted dispersal flux ***(F)*** is a function of recruitment ***(R)*** and dispersal flux ***(f)***, ***F*** is very robust across scales. This is likely a function of patch area and further serves to highlight nodes of ecological importance due to both area and dispersal probability. Figure 11 clearly indicates a linear portion of crucial habitat integral to both habitat and movement between landscape patches for female grizzly bears within the FMFGBRP study area.

Figure 11 – Final landscape graph demonstrating area-weighted flux patch sensitivities and edges with greater than 10 percent probability for dispersal between patches.

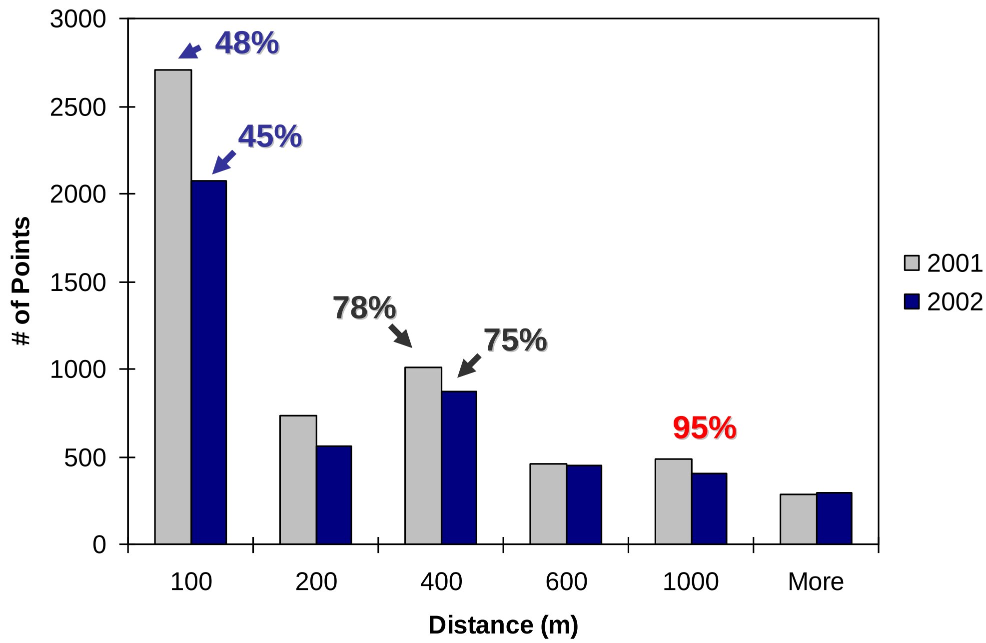


Spatial patterns visible as demonstrated by the landscape level assessment may potentially be missed by habitat level assessments. As such, maintaining patches at both the habitat level and the landscape level scale should be factored into land use management decisions when planning further resource developments.

3.3 Graph Validation

Final graph validation was completed using 2001 and 2002 female GPS location data. Results of the landscape validation procedure indicated that within 100 meters of landscape edges or connections, almost 50 percent of 2001 and 2002 female grizzly bear GPS data were captured. Whereas within 400m of landscape edges, 75 percent and greater of female grizzly bear GPS data were captured (Figure 12). While simply reported, overall results demonstrate that the graph theory landscape structure spatially and functionally does represent grizzly bear data (movement and/or habitat use) within the FMFGBRP study area.

Figure 12 - Histogram showing results of graph validation using 2001 and 2002 female GPS point locations intersected with distance grid with cumulative percentages.



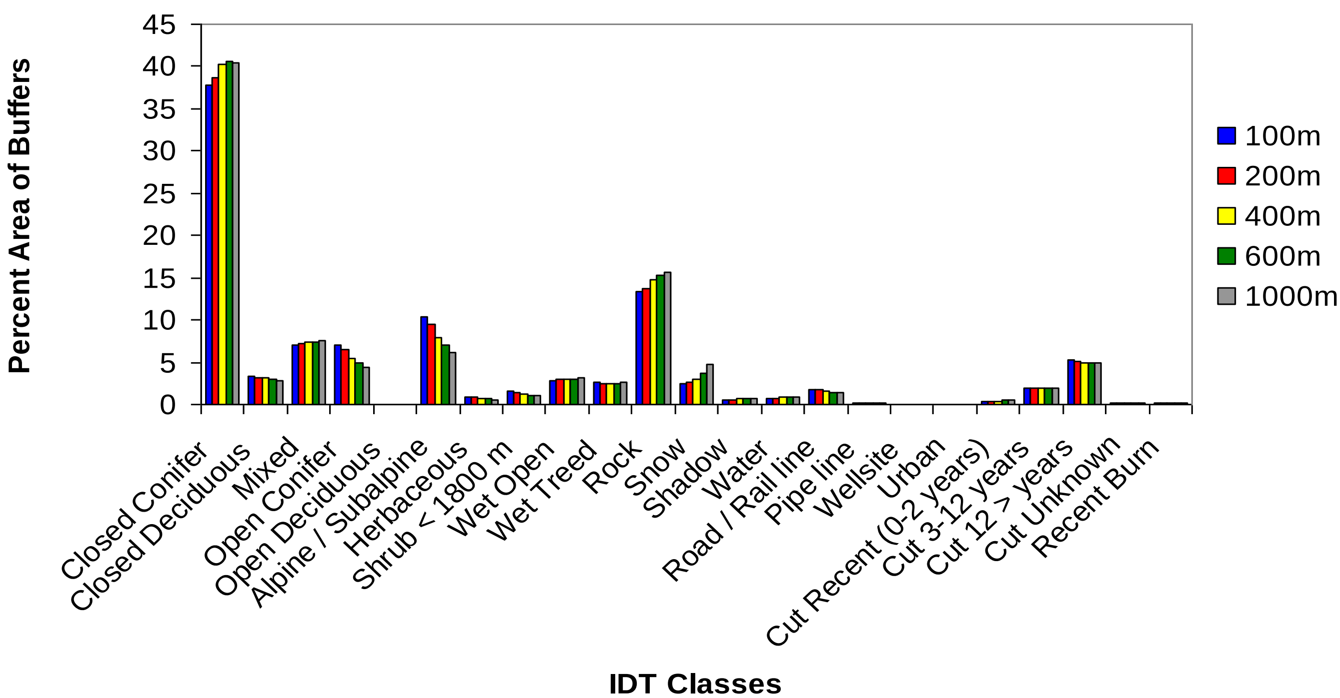
Results of the landscape validation were further segmented by 1) females previously included in 1999 / 2000 model development, and 2) females not previously used in 1999 / 2000 model development (Table 4). Results were similar regardless of year or model development status. No difference in results for females not used in model development strengthens the overall utility of the graph theory approach as applied to female grizzly bear populations. Furthermore, results aid in promoting the graph theory approach presented in this thesis as a predictive tool in landscapes where GPS movement data is unobtainable.

Table 4 – Results of graph validation by females previously used versus females previously not used in model development by year.

	2001 Females Previously Used		2001 Females Previously Not Used		2002 Females Previously Used		2002 Females Previously Not Used	
Buffer	# GPS Points	Cumulative Percent	# GPS Points	Cumulative Percent	# GPS Points	Cumulative Percent	# GPS Points	Cumulative Percent
100	1963	49.94%	744	42.49%	1397	44.35%	676	44.77%
200	493	62.48%	240	56.20%	371	56.13%	192	57.48%
400	659	79.24%	352	76.30%	613	75.59%	260	74.70%
600	263	85.93%	199	87.66%	296	84.98%	152	84.77%
1000	322	94.12%	165	97.09%	262	93.30%	146	94.44%
More	231	100.00%	51	100.00%	211	100.00%	84	100.00%

Results of edge interval buffering demonstrated habitat composition related to LCP connections or potential movement paths between identified RSF habitat patches (Figure 13). In general, changes to buffer size resulted in little change to IDT habitat composition and percent. Slight increases in percent were shown by closed conifer, rock and snow classes. Slight decreases in percent were shown by open conifer and alpine/subalpine classes. Overall, edge structures were predominantly composed of closed conifer forest stands with no occurrence of open deciduous forest stands.

Figure 13 - Histogram showing simple habitat interactions based on buffering intervals.



4.0 DISCUSSION

The graph theoretic model as presented here can be used as an analytical tool for conservation planning. The approach provides important information regarding habitat patch sensitivities to removal, edge properties relating to corridor identification and overall connectivity measures the study area landscape (Figure 11). Additionally, the graph theory approach has the ability to identify habitat patches and movement paths most sensitive to development and furthermore important to overall conservation efforts.

Bear behavior in general can be difficult to model as each individual bear behaves differently. However, when combined with RSF models the graph theoretic model incorporates bear biology specific to habitat selection. As such, the graph theoretic model included aspects of both general foraging and movement behaviors specific to female grizzlies. As LCP modeling and thus edge connections were intended to reflect movement, specific emphasis was made to validate this portion of the research.

Iterative removal of habitat patches or nodes was shown to affect both spatial dispersal patterns and resulting connectivity rates. As habitat patches were removed from the home range a bear's ability to traverse the landscape was shown to decrease (MINEND / ENDNODE). However, this was dependant on habitat patch size and placement within the landscape. For example, patches on the periphery had a limited effect while patches central to the graph structure were of greater importance.

The threshold distance or the distance at which connectivity decreased to the point where a graph disconnects into subgraphs was identified 2.5 km for the FMFGBRP landscape. The identification of critical thresholds must be interpreted with caution as the measures presented here were not related to female movement. The results indicated by the graph theory approach are based solely on the spatial configuration of habitat patches and corresponding distance of edge connections between nodes.

REFERENCES