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USING WEIGHTED DISTANCE AND LEAST-COST CORRIDOR ANALYSIS TO EVALUATE REGIONAL-SCALE LARGE CARNIVORE HABITAT CONNECTIVITY IN WASHINGTON

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Abstract: Population fragmentation and isolation are primary concerns for conservation of large carnivores. Highways are often important landscape features contributing to regional-scale habitat fragmentation for these species. We used GIS weighted distance and least-cost corridor techniques to map relative landscape permeability and landscape linkages for large carnivores in Washington and adjacent portions of Idaho and British Columbia. Landscape permeability was modeled based on land cover, road density, human population density, and topography. We identified six concentrations of large carnivore habitat, including the British Columbia Coast Range, the North Cascades, the South Cascades, the Kettle-Monashee Ranges, the Selkirk-Columbia Ranges, and the Olympic Mountains. The model highlighted four landscape linkage areas of potential importance for large carnivores including the Fraser River area (B.C.), Snoqualmie Pass (Wa), the Okanogan Valley (Wa. and B.C.), and the Upper Columbia River area (Wa. and B.C.). We also modeled landscape linkages in southwestern Washington, between the South Cascades and Olympics, however the resistance to movement in this landscape was extremely high. We expect that southwestern Washington is impermeable to long-distance movements for our focal species. GIS overlays of the Washington state highway network on our landscape permeability and linkage maps indicated that, in the vicinity of the Cascades and northeastern Washington, 497 miles (800 km) of state highway passed through areas accessible to large carnivore intra-territorial movement, and 234 miles (377 km) of state highway passed through landscape linkage areas that may be important for inter-territorial movement. [Funding for this project was provided by the Washington State Department of Transportation, and the USDA Forest Service, PNW Research Station under the Northwest Forest Plan.]

Introduction

Loss of habitat, human-caused mortality, and isolation of small populations are major concerns in the conservation of large carnivores (Clark et al. 1996, Noss et al. 1996). Highways, human activities, and developments along transportation corridors are important factors contributing to these problems (e.g., Evink et al. 1999, 1998, and 1996). In order to address these issues for conservation planning in Washington state, we evaluated relative landscape permeability in relation to highways for large carnivores in Washington and adjacent portions of Idaho and British Columbia.

Our objectives for this project were to 1) develop regional-scale GIS modeling techniques to evaluate multi-species large carnivore habitat connectivity, 2) apply the model to Washington and adjacent areas, and 3) identify Washington state highway segments that intersect potential large carnivore habitat and linkage areas. The focal species for this project were the four endangered, threatened, or sensitive large carnivores listed for Washington: gray wolf (*Canis lupus*, endangered), wolverine (*Gulo gulo*, sensitive), lynx (*Lynx canadensis*, threatened), and grizzly bear (*Ursus arctos*, threatened). Status of these species in Washington was recently summarized by Gaines et al. (2000). We expect that the habitat connectivity patterns identified for these species will be important for a wide variety of other wildlife species as well.

Our goals for this project were not only to identify possible habitat corridors in the landscape, but also to broadly evaluate landscape permeability from the perspective of large carnivore movement. As an uncommon ecological term, landscape permeability warrants a definition. Forman and Godron (1986, p. 594) define a landscape as “a heterogeneous land area composed of a cluster of interacting ecosystems that are repeated in similar form throughout.” *Webster’s* dictionary defines permeability as “the state or quality of being open to passage or penetration”. Thus, from an animal movement perspective, we would define landscape permeability as “the quality of a heterogeneous land area to provide for passage of animals”. In contrast to focusing on the identification of corridors, the broader evaluation of landscape permeability provides an estimation of relative potential for animal passage across the entire landscape, including the identification of potential barriers to animal movement.

When discussing animal movement and landscape permeability, it is important to be clear about the type of movement that is being considered. Animal movements can be broadly categorized into two classes (Swingland and Greenwood 1984): 1) intra-territorial movements, short and medium distance movements in or near an established home range, usually associated with foraging, reproduction, or seasonal shifts in habitat, and 2) inter-territorial movements, long distance dispersal or exploratory movements outside of an established home range, usually associated with investigations of distant habitat areas or the establishment of new home ranges. Landscape permeability to intra-territorial movement determines what resources are available to an animal in its daily or seasonal movements. This resource availability influences survival and reproduction (Morrison et al. 1998). Landscape permeability to inter-territorial movement determines the level of demographic interchange and gene flow between groups of animals and the ability of animal populations to become established in unoccupied suitable habitat (referred to as metapopulation dynamics, Hanski and Gilpin 1997). Landscape management in consideration of both types of movement is important for the long-term conservation of large carnivores (Noss et al. 1996).

Study Area

We focused on evaluating landscape permeability in the state of Washington. However, to effectively evaluate landscape permeability in Washington, linkages to habitat concentration areas in a larger region needed to be addressed. Our analysis encompassed all of Washington and adjacent portions of Idaho and British Columbia (figure 1). The analysis area extended from the Oregon-Washington border (latitude 42°) north to Revelstoke and Kamloops, British Columbia (latitude 51°), and from the Pacific Coast (longitude 125°) east to the Idaho-Montana border (longitude 116°). This analysis encompassed approximately 125,740 miles^2 (325,667 km^2).

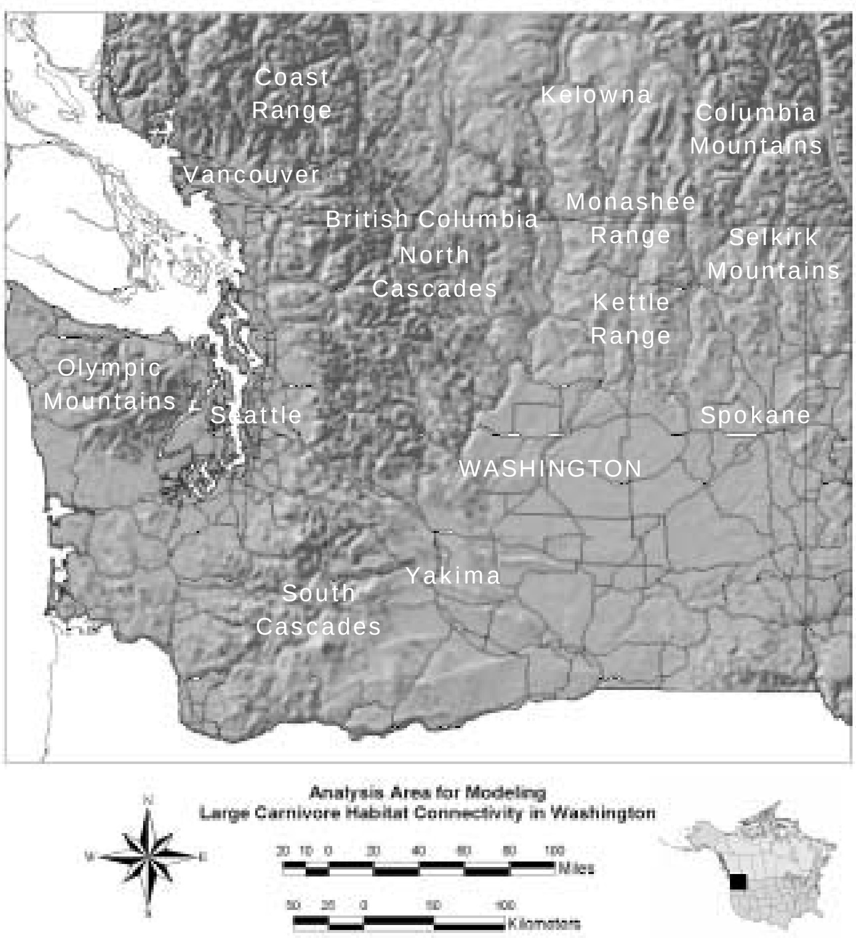

Fig. 1. Analysis area for modeling large carnivore habitat connectivity in Washington.

Broad-scale landscape patterns in Washington and adjacent portions of Idaho and British Columbia are largely defined by the gross geological features that dominate the region (Johnson and O'Neil 2001). In particular, the north-south spine of the Cascade Range runs from the Columbia River east of Portland into British Columbia east of Vancouver, and shifts west into the Coast Range along the Fraser River in southern British Columbia. These mountains substantially influence the climate, vegetation, and human development in the region. West of the Cascade Range, moist coastal conifer forest and extensive urban development characterize the Puget Sound and Seattle area. Southwestern Washington and the Olympic Peninsula are also characterized by moist coastal conifer forest, much of which is in private land ownership and managed for industrial timber production. The Olympic National Park and some surrounding National Forest lands provide an isolated block of less disturbed habitat on the Olympic Peninsula. Relatively arid conditions dominate the agricultural and shrub-steppe landscapes of the Columbia Basin, east of the Cascade Range. These arid conditions extend north in a narrow strip along the Okanogan Valley into central British Columbia. Northern portions of the Okanogan Valley are heavily developed, particularly along Okanagan Lake, where the cities of Penticton, Kelowna, and Vernon are located. East of the Okanogan Valley, in British Columbia and northeastern Washington, the Kettle and Selkirk Mountain Ranges extend south from the Monashee and Columbia Mountains. These low mountains are characterized by mixed interior coniferous forest.

Methods

We used GIS weighted distance and least-cost corridor analyses to evaluate landscape permeability for large carnivores. These techniques are based on the idea that each cell in a map can be given a relative "cost" associated with moving across that cell (ESRI 1992). The "cost" of moving across a cell is calculated as the cell size (in meters) times a weighting factor based on the dispersal habitat suitability of the cell (table 1, figure 2).

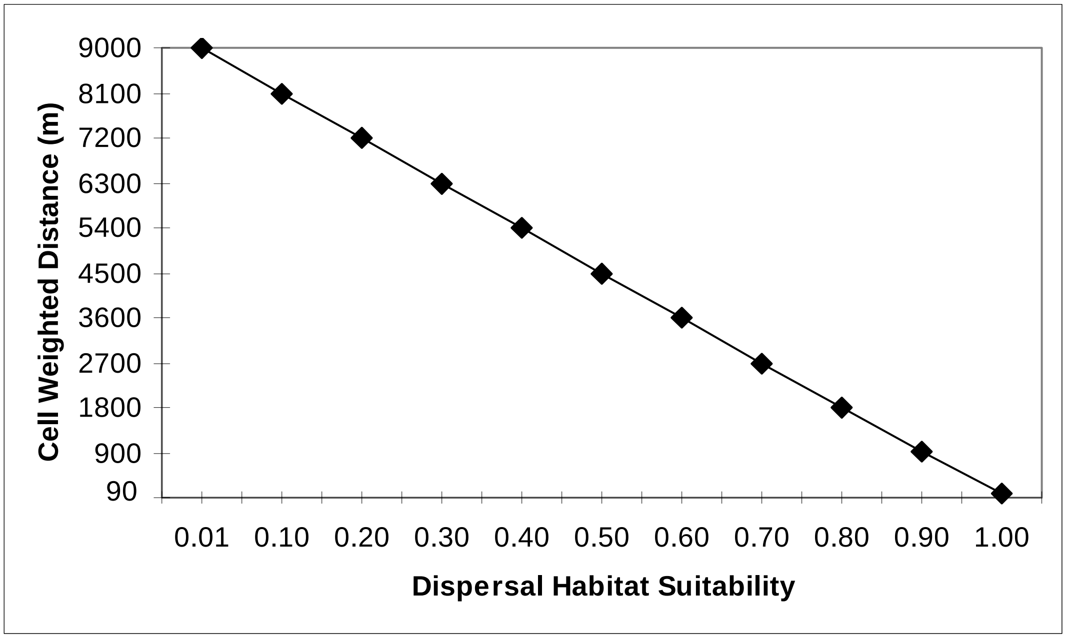

Fig. 2. Map cell weighted distance in relation to dispersal habitat suitability for weighted distance and least-cost corridor analysis of landscape permeability. The weighted distance for moving across each cell was calculated as: cell size x (100-(100 x (dispersal habitat suitability)). Cells with a dispersal habitat suitability of 1.00 were attributed with a weighted distance of 90 m. All weighted distance and least-cost corridor analysis was conducted using a 90 m cell size.

Table 1
Dispersal habitat suitability model parameters and permeability values for weighted distance and least-cost corridor analysis. Permeability scores of 1.0 are most permeable, scores of 0.1 are least permeable. Dispersal habitat suitability within each map cell was calculated as the product of the permeability score for each landscape characteristic at the cell: Dispersal habitat suitability = (land cover class) x (population density) x (road density) x (slope).

	Relative Permeability by Species				
Landscape Characteristic	**General Forest Associate**	**Gray Wolf**	**Lynx**	**Grizzly Bear**	**Wolverine**
Land Cover Class					
Agriculture	0.3	0.4	0.3	0.3	0.3
Alpine	0.8	1.0	0.8	1.0	1.0
Dry Forest	1.0	1.0	1.0	1.0	1.0
Dry Shrub/grass	0.8	1.0	0.8	0.5	0.5
Interior Mesic Forest	1.0	1.0	1.0	1.0	1.0
Interior Mesic Shrub	0.8	1.0	0.8	0.8	0.6
Snow / Ice	0.1	0.1	0.1	0.1	0.8
Urban / Developed	0.1	0.1	0.1	0.1	0.1
Water	0.1	0.1	0.1	0.1	0.1
West-side Mesic Forest	1.0	1.0	1.0	1.0	1.0
West-side Mesic Shrub	0.8	1.0	0.8	0.8	0.6
Wetland / Riparian	1.0	1.0	0.8	1.0	0.8
Bare Ground	0.3	0.6	0.3	0.3	0.8
Population Density (people/mi^2)					
0 – 10	1.0	1.0	1.0	1.0	1.0
10 – 25	0.8	0.5	1.0	0.5	0.8
25 – 50	0.5	0.3	0.8	0.3	0.5
50 – 100	0.3	0.1	0.5	0.1	0.5
100 – 100000	0.1	0.1	0.1	0.1	0.1
Road Density (mi/mi^2)					
0 – 0.01	1.0	1.0	1.0	1.0	1.0
0.01 – 1	1.0	1.0	1.0	1.0	1.0
1 – 2	0.8	0.8	1.0	0.8	0.8
2 – 4	0.6	0.5	1.0	0.5	0.5
4 – 6	0.5	0.5	0.8	0.3	0.5
6 – 8	0.4	0.2	0.8	0.2	0.2
8 – 10	0.2	0.2	0.8	0.2	0.2
10 – 50	0.1	0.1	0.1	0.1	0.1
Slope (%)					
0 – 20	1.0	1.0	1.0	1.0	1.0
20 – 40	0.8	0.8	0.8	1.0	0.8
>40	0.6	0.6	0.6	1.0	0.6

For example, movement across a cell with good dispersal habitat characteristics (dispersal habitat suitability = 1.0) would accrue a “cost” of 90 m (0.09 km), while movement across a cell with very poor dispersal habitat characteristics (dispersal habitat suitability = 0.01) would accrue a “cost” of 9000 m (9 km). Weighted-distance analysis calculates, for each cell, the minimum sum of cell “costs” between the cell in question and a designated source area. This results in a map of relative landscape permeability, showing the cumulative cost (in weighted meters or kilometers) of movement away from the designated source. Least-cost corridor analysis calculates, for each cell, the minimum cost of moving between two sources, for the least costly route passing through that cell. The least-cost corridor analysis results in a map that shows the best landscape linkages between the designated source areas. Other researchers that have employed these techniques for the evaluation of animal movement routes include Walker and Craighead (1997), Kobler and Adamic (1999), and Purves and Doering (1999).

We developed dispersal habitat suitability models for each of the four focal species (wolves, wolverine, lynx, and grizzly bears) based on an extensive literature review (Singleton et al. in prep.). We then developed a general large carnivore model, based on the parameters identified for the species-specific models, to provide a single generalization of the landscape patterns identified by the species-specific models. This paper presents the general large carnivore model. Results of the species-specific models are presented in Singleton et al. (in prep.).

We compiled GIS data sets representing land cover class, roads, highways, human population density, and topographic characteristics for our analysis area from a variety of sources, using approximately 1:250,000 mapping scale source data. We used a 90 meter raster cell size for all weighted distance and least-cost corridor analysis. All spatial analysis was conducted using ArcInfo 8.0.2 GIS software (ESRI 2000) in a Windows NT environment. Base layer metadata and spatial analysis AML programs are available in the project report (Singleton et al. in prep.).

We identified large roadless areas and areas designated in recovery or management plans for the focal species as the habitat concentration areas around which we were interested in evaluating landscape permeability using weighted distance analysis. We refer to those areas within 100 km weighted distance of modeled habitat concentration areas as “available habitat”, indicating that there were not substantial landscape barriers between the evaluated area and a habitat concentration area. Areas identified as “available habitat” may or may not be “suitable habitat” in the sense of providing food, denning sites, or other resources that may be required by the a focal species.

We used weighted distance analysis to map landscape permeability for areas up to 1000 km weighted distance from habitat concentration areas. We expect that areas in excess of 1000 km weighted distance are unlikely to be accessible to individuals of the focal species moving from the habitat concentrations due to the cumulative effects of landscape barriers or filters.

We used least-cost corridor analysis to map landscape linkages in areas between habitat concentrations where maintaining landscape permeability may be a management objective. We refer to these areas of reduced landscape permeability between habitat concentrations as “fracture zones” (*sensu* Servheen and Sandstrom 1993). The landscape within each fracture zone was classified into 10 groups of equal area based on the results of the least-cost corridor analysis. This provides a ranking in 10 percentile increments ranging from the most permeable 10% of the fracture zone landscape (least-cost corridor rank 1) to the least permeable 10% (least-cost corridor rank 10). We report areas within least-cost corridor ranks 1 to 5 as landscape linkages within the fracture zone landscapes.

We calculated an index of relative permeability for each fracture zone by calculating the ratio of the weighted-distance along the most permeable linkage in the fracture zone to the linear distance between the habitat concentration areas. Fracture zone landscapes with weighted distance to linear distance ratios approaching 1 were more permeable on average than landscapes with higher weighted distance to linear distance ratios.

We identified areas where the Washington state highway network could be impacting animal movement by overlaying the state highway system on the landscape permeability map (derived from the weighted-distance analysis) and the landscape linkage map (derived from the least-cost corridor analysis). We used the 100 km weighted distance contour to identify areas where highways pass through “available” habitat and where the focal species may be expected to encounter the highway during intra-territorial movements around the habitat concentration areas. Areas in fracture zones where highways intersect least-cost corridor ranks 1 to 5 are locations where we predict that the focal species are more likely to encounter highways during inter-territorial movements between habitat concentration areas.

Results

The results of our large carnivore dispersal habitat suitability modeling are displayed in figure 3. Our weighted distance analysis showed that there were six clusters of relatively well connected blocks of roadless landscapes or areas identified as being of conservation concern in recovery or management plans for the focal species. These habitat concentration areas included the South Cascades, North Cascades, Coast Range, Kettle-Monashee Ranges, Selkirk Range, and the Olympic Mountains (table 2, figure 4).

Table 2
Habitat concentration area sizes and available habitat identified for the large carnivore model. Available habitat is the area within 100 km weighted distance of a habitat concentration area.

Habitat	Concentration Area Size		Available Habitat	
Concentration Areas	Square Miles	Square Kilometers	Square Miles	Square Kilometers
North Cascades	6736	17446	10806	27986
Coast Range*	3840	9947	5864	15188
Olympics	1457	3772	2384	6175
Kettle-Monashee*	1285	3329	4937	12786
Selkirks*	1175	3043	3102	8034
South Cascades	1115	2888	2374	6150

* These areas extend into areas not fully addressed in this assessment. Sizes listed here should be considered minimums.

The landscape permeability map (figure 4) highlighted five fracture zones between the habitat concentration areas where we were interested in identifying landscape linkages. Results of the least-cost corridor analysis (table 3, figure 5) indicated that the Fraser River (between the North Cascades and the Coast Range) was the most permeable fracture zone between habitat concentration areas, followed by the Upper Columbia Valley (between the Selkirk and Kettle-Monashee Ranges), Snoqualmie Pass (between the North and South Cascades), and the Okanogan Valley (between the North Cascades and Kettle-Monashee Ranges). The southwest Washington-Olympics fracture zone was substantially less permeable than the other fracture zones.

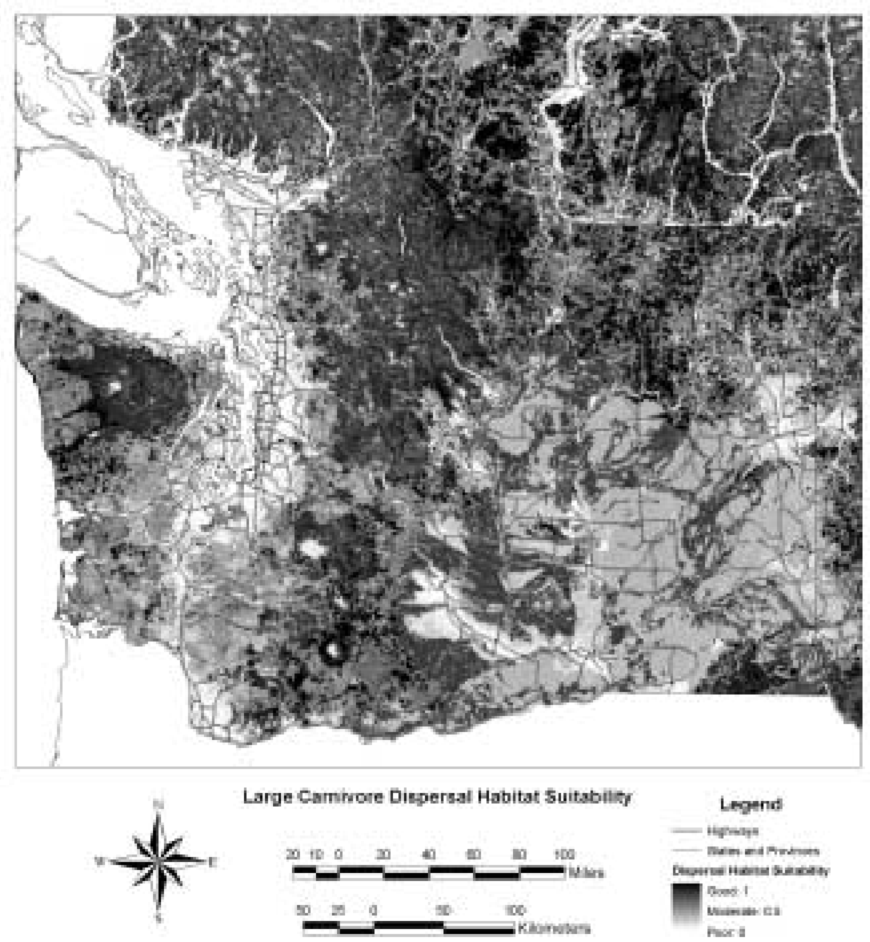

Fig. 3. Large carnivore dispersal habitat suitability based on land cover class, human population density, road density, and slope (table 1). Darker areas are more suitable for large carnivore movement.

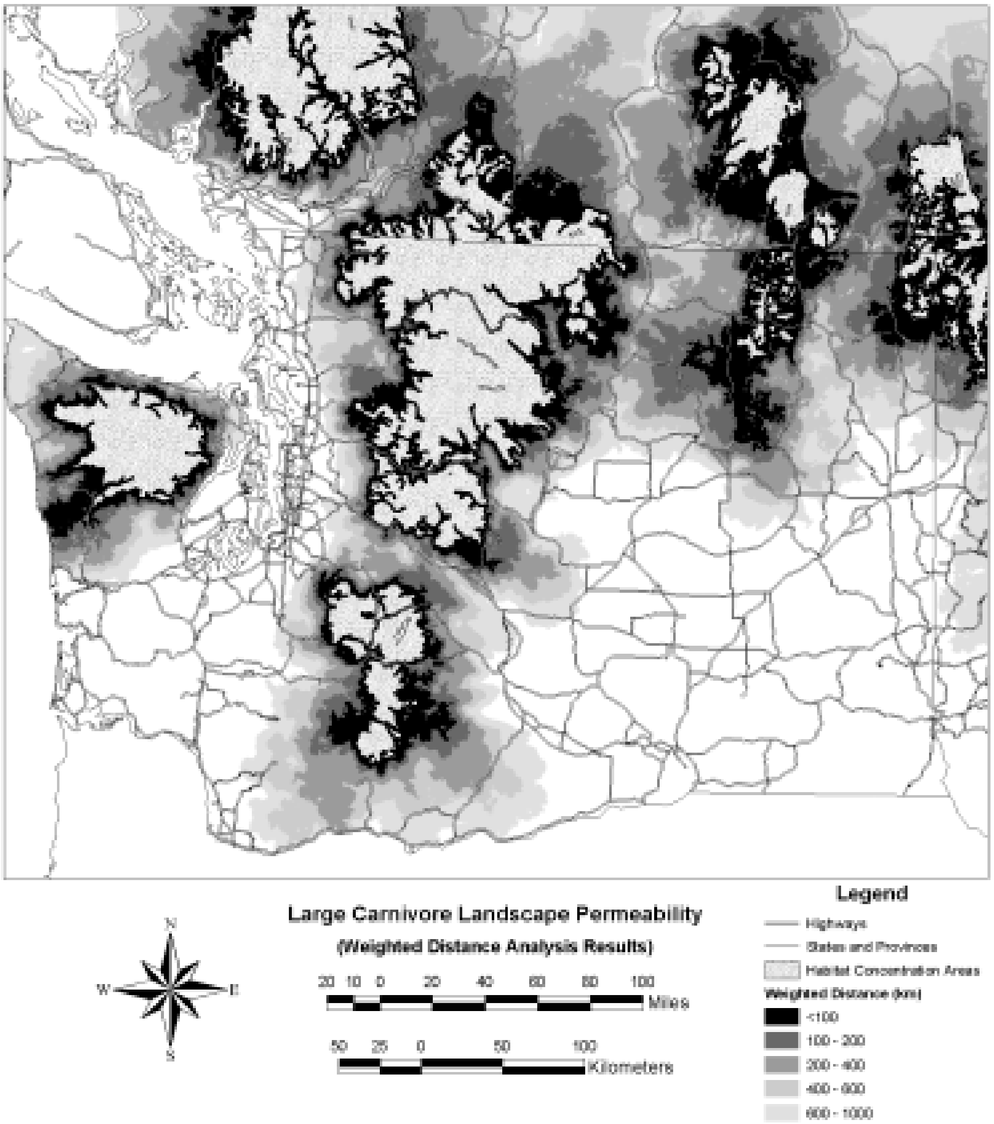

Fig. 4. Large carnivore landscape permeability determined by weighted distance analysis. Weighted distance indicates the cumulative weighted distance from habitat concentrations. Dark areas are more accessible to animals moving from the habitat concentration areas. State highways passing through habitat concentration areas and adjacent accessible habitats (table 4) have the potential to influence intra-territorial movements and be mortality sources for large carnivores.

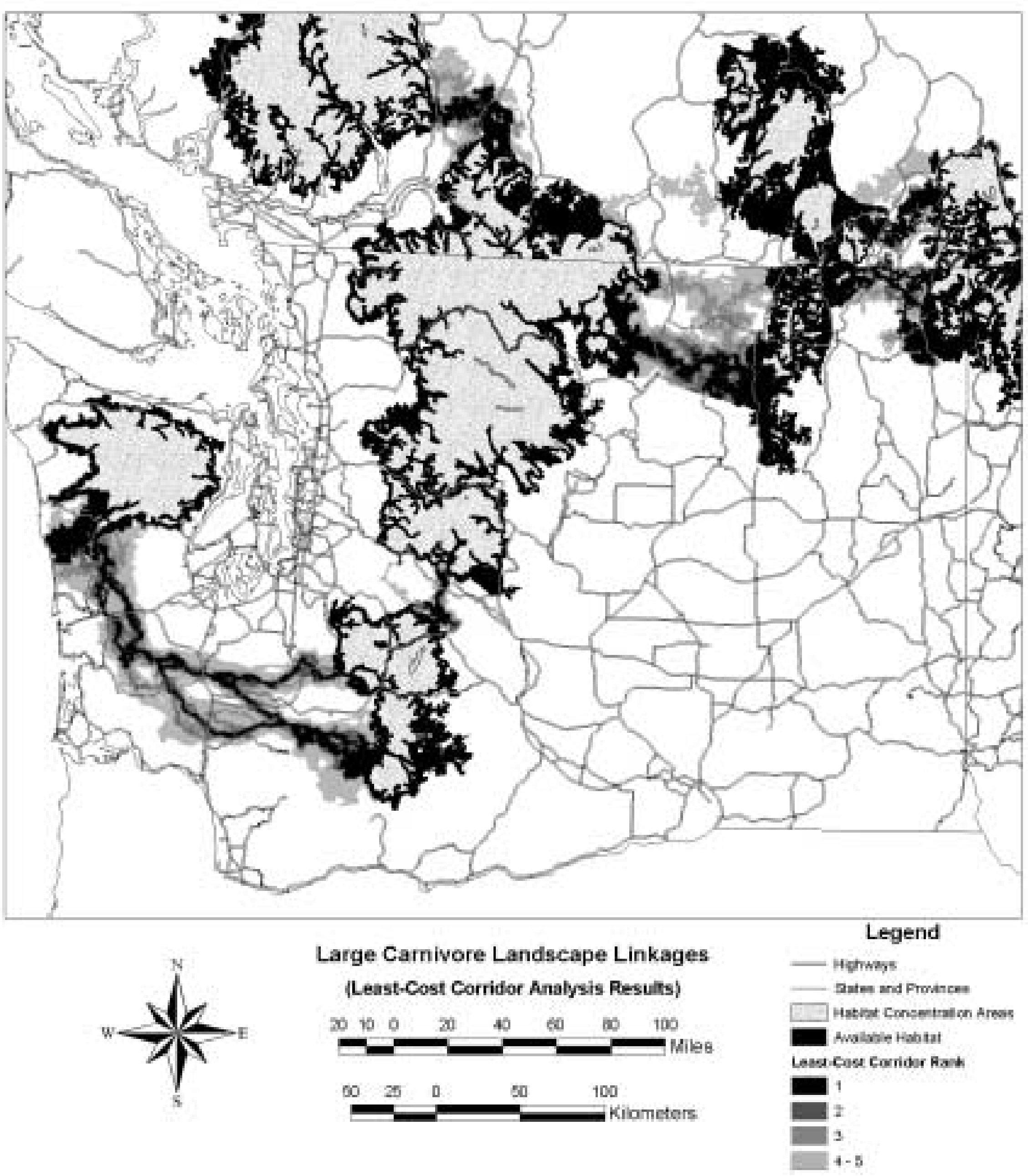

Fig. 5. Large carnivore habitat landscape linkages determined by least-cost corridor analysis. The darkest areas are either available habitat (areas within 100 km weighted distance of habitat concentration areas) or the most permeable landscape linkages between habitat concentration areas. Least cost corridor rank 1 indicates the most permeable 10% of the fracture zone landscape, 2 indicates the next most permeable 10%, etc. State highways intersecting landscape linkages (table 5) have the potential to reduce the permeability of those linkages and restrict inter-territorial movements.

Table 3
Landscape permeability within fracture zones identified by the large carnivore model.

Fracture Zone	Minimum Linkage Weighted Distance (km)	Linear Distance (km)	Weighted Distance / Linear Distance Ratio
Fraser River Canyon	288.1	27.9	10.3
Upper Columbia River	423.5	46.3	9.1
I-90 Snoqualmie Pass	630.4	33.5	18.8
Okanogan Valley	633.5	80.8	7.8
SW Washington	6943.8	116.2	82.6

GIS overlays of the Washington state highway network on the landscape permeability map (figure 4) indicated that 497 miles (800 km) of state highways occur within available large carnivore habitat in the Cascades and northeastern Washington (table 4). An additional 46 miles (74 km) of state highway passes through available habitat on the Olympic Peninsula.

Overlays of the state highway network on the landscape linkage map (figure 5) indicate that 234 miles (377 km) of highway intersect areas identified as the most permeable 50% of the fracture zones in the Cascades and northeastern Washington (table 5), including 82 miles (132 km) in the Upper Columbia River area, 141 miles (228 km) in the Okanogan Valley, and 11 miles (17 km) along Snoqualmie Pass. An additional 313 miles (505 km) of state highway intersects the modeled landscape linkages in southwestern Washington.

Table 4
Highway segments passing through available large carnivore habitat (areas within 100 km weighted distance of large carnivore habitat concentration areas). Minimum and maximum milepost numbers were derived from a GIS overlay of state highway mileposts at five-mile intervals and do not precisely reflect the length of the highway segment.

Habitat Concentration Area	State Route	Length Miles	Length KM	Milepost Min.	Milepost Max.	Description
Kettle-Monashee	20	33.2	53.4	310	340	Republic to Kettle Falls
	21	30.0	48.3	120	155	South of Republic
	21	11.7	18.9	175	190	Republic to Canadian Border
	25	1.2	1.9	120	120	Northport to Canadian Border
	31	15.1	24.3	15	25	Metaline Falls Area
	395	24.6	39.6	255	270	Kettle Falls to the Canadian Border
North Cascades	2	62.3	100.4	35	95	Stevens Pass, Gold Bar to Leavenworth
	20	140.9	148.5	95	190	Concrete to Winthrop
	20	3.3	5.3	215	220	Loup Loup Pass
	90	23.8	38.3	40	50	West Side of Snoqualmie Pass
	97	15.1	24.3	150	175	Blewett Pass
	153	7.8	12.6	15	20	Methow Valley, between Pateros and Twisp
	530	1.7	2.7	65	65	Skagit River
	542	22.5	36.2	35	55	Mt. Baker Highway
	906	1.2	2.0	0	0	Snoqualmie Pass Frontage Road
	970	2.7	4.4	10	10	South of Blewett Pass
Olympic	101	40.8	65.7	115	235	Olympic National Park Vicinity
	109	4.4	7.0	35	35	Olympic National Park Vicinity
	119	0.8	1.2	10	10	Olympic National Park Vicinity
Selkirks	20	12.1	19.5	380	400	South of Ione
South Cascades	12	27.2	43.8	140	170	White Pass, Cowlitz River to Tieton River
	123	16.3	26.2	0	15	East Side of Mt. Rainier National Park
	165	1.0	1.6	0	0	Mt. Rainier National Park
	410	41.4	66.6	55	90	Crystal Mountain to American River
	706	2.1	3.4	10	10	Mt. Rainier National Park

Table 5
Washington state highway segments passing through landscape linkages between large carnivore habitat concentration areas. Minimum and maximum milepost numbers were derived from a GIS overlay of state highway mileposts at five-mile intervals and do not precisely reflect the length of the highway segment.

Fracture Zone	State Route	Length		Milepost		Description
		Miles	KM	Min.	Max.	
Upper Columbia Valley	20	26.4	42.5	380	405	South of Ione
	31	20.2	32.5	5	20	Metaline Falls Area
	25	18.6	29.9	95	115	North of Kettle Falls
	395	17.0	27.4	255	270	North of Kettle Falls
Okanogan Valley	97	25.6	41.2	280	315	Omak to Oroville
	21	51.5	82.9	125	180	North and South of Republic
	20	47.6	76.6	270	310	East and West of Republic
	155	17.1	27.5	55	7	East of Omak
Snoqualmie Pass	90	10.5	16.9	65	75	Near Easton
SW Washington	101	5.9	9.5	140	150	East of Queets
	101	44.8	72.1	90	135	Hoquiam to Queets
	12	22.2	35.7	0	20	Elma to Aberdeen
	101	14.4	23.2	65	80	Raymond to Aberdeen
	107	7.9	12.7	0	10	South of Montesano
	5	52.4	84.4	55	85	Centralia to Castle Rock
	6	26.7	43.0	20	50	Pe Ell to Chehalis
	7	13.7	22.1	10	20	Elbe to Carlson
	12	25.8	41.5	45	95	I-5 to Mossyrock
	122	8.0	12.9	0	10	Near Mossyrock
	504	14.8	23.8	10	20	Near Toutle
	505	19.2	30.9	0	15	I-5 to Toutle
	506	13.7	22.1	0	10	Near Vader
	507	9.5	15.3	0	10	Centralia to Bucoda
	508	21.0	33.8	0	30	Between Napavine and Morton
	706	13.6	21.9	0	15	Elbe to Ashford

Discussion

The explicit consideration of highways in relation to broad-scale habitat patterns is a critical component of landscape planning. Major highways are often a central landscape feature in valley bottoms and major mountain passes, where they connect human population centers and contribute to changes in the patterns of vegetative communities and human development (Forman 1995). The design of the highway and management of the adjoining landscape to provide for animal movement in a manner that is safe for both animals and motorists are important considerations. However, highways are only one component of broader landscapes configured by topography, vegetation patterns, and human development. Proactive land management that maintains options for directing human development and vegetation management will be important for maintaining or improving habitat linkages at a regional scale for all wildlife.

Our analysis provides explicit maps of estimated landscape permeability and expected linkages, created from a consistent analysis across the entire region. These results can be used to identify priorities for regional conservation planning and further survey and assessment work. While this analysis has limitations associated with the scale and accuracy of the base data and the hypothetical, untested nature of the landscape permeability models, it provides an important first step for regional conservation planning. Our regional-scale analysis is not intended to be a substitute for field surveys and analysis of fine scale geographic information in areas that are important for landscape linkage.

Based on our comparison of the species-specific models with the general large carnivore model presented here, we feel that the general large carnivore model provided an adequate approximation of the broad landscape patterns common to the individual species-specific models (Singleton et al. in prep.). The species-specific models did provide important insights into differences between species in the distribution of habitat concentration areas and available habitat, and differences in estimated landscape permeability within fracture zones. However, the general large carnivore model effectively represented common landscape linkages identified for the focal species.

We identified six habitat concentration areas centered on large roadless landscapes and areas identified in management or recovery plans for the focal species. In Washington, habitat concentration areas and surrounding available habitat generally correspond to montane public lands (usually National Forests or National Parks). The North Cascades was the largest of the habitat concentrations contained within our analysis area. All four of the focal species have been documented in this area (Gaines et al. 2000). The Coast Range, Kettle-Monashee, and Selkirk Ranges were also relatively large habitat concentration areas and extend well to the north, beyond our analysis area. The South Cascades and Olympics habitat concentrations were substantially smaller areas.

Four significant landscape linkage areas for large carnivores were identified through our analysis. The Fraser River fracture zone, between the Coast Range and the North Cascades had the shortest linear distance between habitat concentration areas (28 km) and also had the lowest weighted distance (288 km, 10.3 weighted distance to linear distance ratio, table 3). The Upper Columbia River fracture zone (between the Selkirk and Kettle-Monashee Ranges) and Okanogan Valley fracture zone (between the Kettle-Monashee Ranges and the North Cascades) had somewhat longer linear distances between habitat concentration areas, but their overall landscape permeability through the modeled linkages were slightly better than the Fraser-Coquihalla (weighted distance to linear distance ratios were 7.8 for the Okanogan Valley and 9.1 for the Upper Columbia River). The I-90 Snoqualmie Pass fracture zone between the North and South Cascades was relatively short (33 km linear distance), however very high road density and fragmented forest cover through the modeled linkage reduced the estimated landscape permeability (weighted distance 630 km, weighted distance to linear distance ratio 18.8). The I-90 Snoqualmie Pass area was the only fracture zone where field surveys and finer scale linkage modeling have been conducted to assess landscape permeability (Singleton and Lehmkuhl 2000). The landscape linkage highlighted by our large carnivore model corresponded to the primary linkage area along I-90 at Easton Hill identified by Singleton and Lehmkuhl (2000).

We also conducted least-cost corridor analysis on the southwestern Washington fracture zone between the South Cascades and Olympics. Due to the long distance between these habitat concentration areas (116 km) and high resistance to movement (minimum weighted distance through the fracture zone was 6944 km), we believe that the southwestern Washington landscape is an effective barrier for the focal species. Maintaining or developing landscape linkages in southwestern Washington for other species (e.g. black bear (*Ursus americanus*), elk (*Cervus elaphus*), and American marten (*Martes americana*)) may be a worthwhile landscape management objective, however landscape linkage analysis for those species should include linkages between blocks of habitat within southwestern Washington, including Washington Department of Natural Resources lands and industrial timber lands covered by habitat conservation plans for late successional forest species, in addition to roadless areas in the Olympics and South Cascades.

Future survey needs and research opportunities highlighted by our analysis include evaluating historic habitat distribution and linkage conditions, using higher resolution GIS data to evaluate the individual predicted linkages, conducting field surveys for verification of the modeled linkage areas, and using the predictions of these models to develop testable hypotheses for basic research on animal movement and habitat selection. Our analysis has focused on assessing existing regional landscape patterns that have the potential to channel animal movement. As such, it is only one component to contribute to the development of a regional approach to managing large carnivore habitat.

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