Mapping Habitat Connectivity for Greater Sage-Grouse in Oregon's Sage-Grouse Conservation Partnership (SageCon) Assessment Area

Final report to the **Bureau of Land Management**
in partial fulfillment of Cooperative Agreement L12AC20615

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The Nature Conservancy in Oregon
Aaron Jones

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Cover photo: Tatiana Gettelman

Figures and Tables

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PROJECT RATIONALE AND OBJECTIVES

The Greater sage-grouse *(Centrocercus urophasianus,* hereinafter referred to as "sage-grouse") is regarded as a focal species for conservation of sagebrush steppe and Great Basin sagebrush communities due in part to its broad range, its selection for habitat across multiple scales, and the wide-spread conversion, degradation, and fragmentation of this habitat. Habitat connectivity – the extent to which a landscape allows for movements of a species between vital resources, breeding locations, or among populations – is important to the survival of individuals, the maintenance of genetic diversity, and the long-term persistence of metapopulations. To support genetic exchange for long-term population viability, there is a recognized need to facilitate range-wide sage-grouse movement between Primary Areas for Conservation (PACs, USFWS 2013; also referred to as "core areas" by Hagen, 2011) and areas of >= 75% Breeding Bird Densities ("BBD areas", Doherty et al. 2010).

In support of the Sage-Grouse Conservation Partnership (SageCon) in its development of a comprehensive plan for maintaining and improving sage-grouse populations and habitats in Oregon and to provide the Bureau of Land Management (BLM) with data products for related project-level planning and analysis, The Nature Conservancy analyzed sage-grouse habitat connectivity in the SageCon Assessment Area of southeastern and central Oregon (Fig. 1). The study was initiated to help inform sage-grouse habitat conservation and restoration priorities in light of the need to preserve, enhance, and/or restore habitat connectivity between leks and lek complexes. The Advisory Team of sage-grouse biologists was identified early in the process to guide model design and development as well as to review and interpret model outputs.

Analytical Approach

The primary goal for mapping habitat connectivity was the identification of areas important to sage-grouse movement between core areas and leks in the intervening landscape mosaic. Our approach involved the following general steps: 1) model the area surrounding each target lek to describe its relative accessibility for a female sage-grouse moving away from the lek; 2) identify the lower cost *linkage zones* between each pair of leks based on landscape structure; 3) within the lower cost linkage zones, locate areas where movement of sage-grouse across linkages may be constrained; and 4) within the lower cost linkage zones, identify specific areas of fragmentation which may provide habitat restoration opportunities.

To implement our analyses we leveraged four existing modeling tools that have been applied and tested in similar studies of habitat connectivity: 1) the Conservation Assessment and Prioritization System (CAPS) Traversability metric R script (Compton 2014) and resistant kernel method as detailed in McGarigal et al. (2012); 2) Linkage Mapper (McRae and Kavanagh 2011); 3) Circuitscape (McRae and Shah 2009); and 4) Barrier Mapper tool (McRae 2012a). Using the resistant kernel algorithm (Compton 2014), we first calculated a traversability metric by which to define *lek kernels*, localized areas surrounding target leks modeled as being the most accessible to female sage-grouse moving outward from respective leks in search of a suitable nesting site. Second, we used Linkage Mapper to model the continuity of habitat in the landscape mosaic between lek kernels in the form of *least-cost linkages*, with a focus on *those* connecting separate core areas and BBD areas. Third, using Circuitscape by way of the Pinch-point Mapper tool (McRae 2012b), we analyzed connectivity within the linkage zones (as defined by the spatial extent of *normalized least-cost corridors, or* NLCCs) to identify areas where sage-grouse movement may be most constrained or "bottlenecked" (*pinch-points*). Fourth, we used the Barrier Mapper tool to identify areas within linkage zones (*barriers*) that most disrupt structural connectivity and which may conversely represent important habitat restoration opportunities.

The model results can be used in several ways to support planning and management for sage-grouse persistence. Mapped corridors and metrics of relative linkage quality and robustness (see 'Linkage Statistics') can be used in combination with population information and other management factors to help inform prioritization and siting of conservation actions across the study area. Within individual corridors, areas identified as pinch-points may warrant greater attention for habitat protection to maintain linkage connectivity, whereas identified barriers highlight opportunities where habitat restoration could most benefit network connectivity.

Landscape ecologists often distinguish between *structural* and *functional* (*habitat) connectivity.* Structural connectivity *(*or, *continuity),* long associated with traditional *least-cost path* analyses and the *patch-corridor-matrix* model of landscapes (Forman 1995), characterizes the spatial configuration of habitat types across a landscape without attempting to quantify the likelihood of movement by individuals through that landscape (With 1999; Crooks and Sanjayan 2006). Functional connectivity refers to the interaction of ecological flows (in this case, species movement) with landscape composition and spatial configuration. Functional approaches to habitat connectivity modeling seek to characterize how individuals of a species may progressively perceive, interact with, and move through the landscape mosaic (Jones 2004; Crooks and Sanjayan 2006). Fagen and Calabrese (2006) have further distinguished between metrics of *potential functional connectivity*, which are based on landscape structure and basic information about a focal species' dispersal abilities, and metrics of *actual functional connectivity*, which derive from empirical data on movements of individuals.

Our investigation incorporates metrics of both structural and potential functional connectivity. First, least-cost path and corridor analyses represent the classic approach to modeling structural connectivity. Second, although the resistant kernel algorithm includes a least-cost path component, it describes potential functional connectivity through use of a dispersal parameter (*bandwidth*) and by allowing for the incorporation of nonlinear ecological distance relationships in determining kernel shape and size (Compton et al. 2007). Third, our application of Circuitscape also explores structural continuity, though more holistically than in least-cost path analyses; here, algorithms from circuit theory are used to calculate the expected ecological flow of a species (sage-grouse) between patches (lek kernels) across *all possible paths* of a landscape mosaic (McRae et al. 2008). While there were insufficient data on sage-grouse across our analysis extent to support modeling of actual functional connectivity, our models of potential functional connectivity should nevertheless be evaluated and validated with more localized empirical data where available, including telemetry.

The modeling techniques used in this study are derived from a well-established body of literature and static (atemporal) modeling tools that define habitat connectivity in terms of the support for continuous movement of a focal species at or near ground level through the landscape mosaic. In all such approaches, it is important to establish a reasonable match between the resolution and accuracy of one's input data and the spatial scales at which a target species is thought to interact with a landscape. If this correspondence is called into question, then so must the attempt to track the physical continuity of habitat.

For birds and other flying species, habitat connectivity does not presuppose such explicit structural continuity, but rather a configuration of intermittent habitat patches that function as "stepping stones" for migratory movement and/or dispersal. Although sage-grouse may be less affected than most terrestrial species by fine-scale habitat fragmentation and disturbance over short distances, they are a low-flying species that is inhibited nonetheless by terrestrial barriers such as power lines. Telemetry studies have shown that sage-grouse most often travel in abbreviated bursts – characteristics that entail more frequent interaction with landscape pattern and a reliance on more proximate habitat patches. Further evidence of this is seen in avoidance of agricultural lands and other human development; sage-grouse movements have been found to deviate markedly from straight-line routes in favor of "lesser cost" routes in or near to shrub-steppe vegetation (Schroeder and Vander Haegen 2003). Smith (2010) also found sage-grouse to move in a series of small steps (less than 10 miles per day) over long-distance migrations, utilizing available habitat over their entire route.

DATA PRODUCTS

Readers with access to ArcGIS software may utilize this report's companion GIS content, including: a geodatabase, GIS layer ("lyr") files with prescribed classifications and symbology, and map document. See:

https://s3-us-west-1.amazonaws.com/orfo/deserts/SageGrouseConnectivity.zip

METHODS

Analysis Area

Our analysis area is centered on the Assessment Area of Oregon's Sage-Grouse Conservation Partnership (SageCon) which encompasses the majority of the range of sage-grouse and sagebrush habitats in southeastern and central Oregon. To avoid edge-effects in model results near the SageCon area boundary and to more effectively model habitat connectivity into surrounding lands, we extended our analysis scope across a 10-mile buffer, which includes portions of California, Nevada, and Idaho, resulting in an analysis area of 30,212,760 acres (Fig. 1).

Land ownership in the study area is comprised of 72% public and 28% private lands (NLCD). The majority of public land is managed by the BLM (63.1% of public lands, 45.4% of the study area) across four Districts in Oregon – Vale, Burns, Lakeview and Prineville – and five Districts in adjacent states: Boise and Coeur d'Alene (Idaho); Elko and Winnemucca (Nevada); and Northern California (California and Nevada). With the exception of Humboldt National Forest in Nevada, lands overseen by the USFS (28.1% of public lands, 20.2% of the study area), occur along the study area's northern and western reaches. Lands overseen by the USFWS (3.4% of public lands, 2.4% of the study area) include three large Refuges: Malheur and Hart Mountain NWRs in Oregon, and the Charles Shelton NWR in Nevada. Collectively, the Oregon Department of State Lands (DSL) and Idaho DSL manage an extent comparable to the USFWS (3.3% of public lands, 2.4% of the study area), with jurisdiction of the remaining public lands split primarily between Idaho Department of Fish and Game (IDFG), joint agency ownership, and the Bureau of Indian Affairs (BIA).

The majority of the analysis area occurs within the southern portion of the Columbia Plateau Ecoregion, where extensive high desert plateaus of sagebrush steppe are dominated by various sagebrush species and bunch grasses. Juniper woodlands once limited to rocky, fire resistant sites have expanded throughout the ecoregion, particularly at higher elevations and deeper soil sites. To the north and into the Middle Rockies - Blue Mountains Ecoregion, sagebrush grasslands in intermontane valleys transition first into lower elevation forests dominated by Douglas fir, grand fir and ponderosa pine, then into high country dominated by lodgepole pine, subalpine fir, and whitebark pine. To the west, the East Cascades – Modoc Plateau Ecoregion extends down from the Cascade Crest. Here, cooler and wetter conditions support extensive ponderosa pine forests in the mountains and valleys, and flatlands host large marshes and juniper woodlands mosaicked with increasing sage-steppe towards the east.

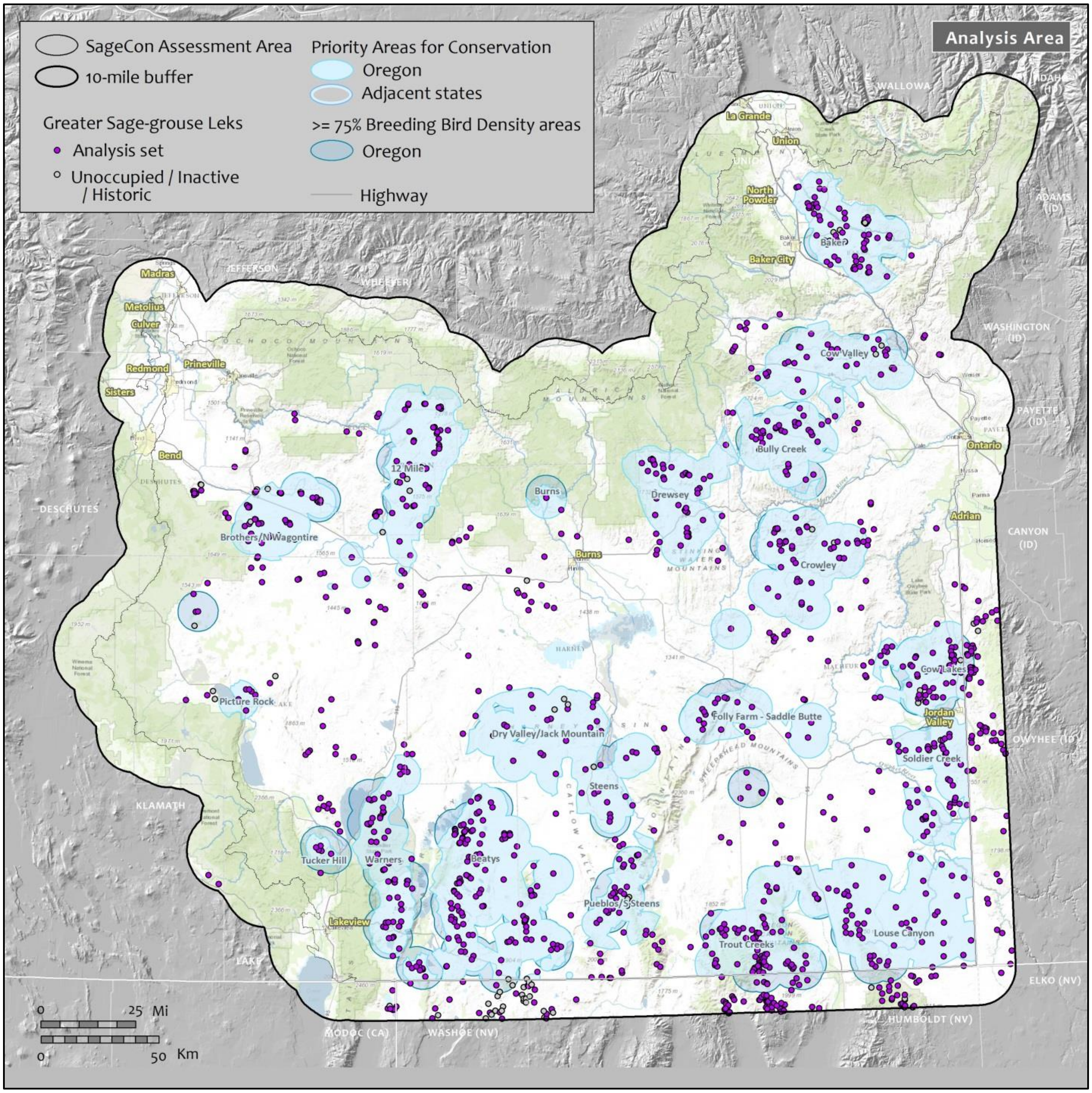

Figure 1: SageCon Assessment Area of Southeastern and Central Oregon

Defining an Analysis Network

While our overarching analytical approach is well-established in landscape ecology literature (Crooks and Sanjayan 2006), framing a suitable conceptual model for the Oregon analyses required early guidance from the Advisory Team. The pivotal decision concerned 'what to connect'; that is, 'How should the *nodes* of the analysis network be defined?' Several possibilities were considered, including equating nodes and/or disjunct clusters of nodes (*constellations*) with core areas, seasonal use areas, populations, or individual leks. The Advisory Team made the early determination to base network nodes on individual leks rather than polygonal core areas in order to preserve the leks' higher spatial precision and strict biological basis.

Consideration was then given to whether the model would explicitly account for intra-seasonal movements by sage-grouse, whereby network linkages might be identified between constellations of leks and/or telemetry relocations as grouped by nesting, brood-rearing, and wintering activity. The team concluded that incorporating seasonality into the model design was unlikely to yield more insight than would an atemporal treatment of individual leks and applying knowledge of seasonal use to the interpretation of resulting models.

The team also weighed the potential value of population-specific models whereby lek constellations would be defined using data on sage-grouse population sizes; however, they concluded that a network constructed purely between un-clustered, individual leks should produce the most readily interpretable model results with the fewest assumptions. Considerations of gene flow between known populations may best be addressed in this case – as with questions of seasonal habitat use – at the stage of model interpretation.

Linkages which connect lek pairs occurring *within* core areas were ultimately withheld from analysis in light of the Advisory Team's recognition that these core areas are already regarded as key habitat for sage-grouse conservation and that their internal linkages are presumed to be presently well-connected for unrestricted sage-grouse movement. In addition, we have set aside analysis of specific linkages *outside* of core areas characterized by straight-line distances which are less than or equal to the straight line distances observed *within* core areas (mean = 6.4 km, st.dev. = 6.4 km; see 'Network Refinement'). The assumption here is that birds may easily fly such distances without necessarily being impeded by habitat fragmentation on the ground. Across the remaining *refined* analysis network we make the assumption that sage-grouse interact with the landscape mosaic at scales commensurate with our use of a 30-meter modeling resolution.

All combined, these decisions provided the basis for the topology of the analysis network. Next, a resistance surface was developed to characterize the intervening landscape mosaic between source and destination habitat areas (nodes in the analysis network). As before, recommendations from the Advisory Team during this phase were critical in guiding appropriate model parameterization and calibration.

Resistance

A resistance surface is a raster-based representation of a landscape wherein each cell value signifies the relative cost associated with hypothetical movement through the cell by an individual of the focal species. (Often, resistance values are alternately interpreted as the inverse of scores for habitat suitability).

Developed with direct involvement of the Advisory Team and built out at a 30-meter resolution, the resistance (or, "cost") surface is the first data product from this analysis and the foundation upon which all subsequent modeling results rely. Together with the target set of leks, it directly informs the definition of both source and destination habitat patches for sage-grouse (see 'Lek Kernel Development') and cost-weighted distances (CWDs, in kilometers) measured outward from them.

The first step in construction of the resistance surface involved identification of variables that impede (create resistance to) movement of the focal species, selection of associated spatial datasets (e.g., roads, tree canopy cover, agriculture), and characterization of three types of resistance based on consequences to sage-grouse: 1) incurred energetic costs and movement difficulty, 2) increased mortality risk, and 3) increased behavioral avoidance (Table 1). Each type of resistance was then defined by a combination of variables. Energetic cost and movement difficulty were represented as the inverse of values in a habitat layer developed from several landcover variables, including: agriculture, existing vegetation type, fire, invasive species, and tree canopy cover (Table 2 and Fig. 2). Variables contributing to increased mortality risk included: housing density, communication towers, surface mining, pipelines, power plants, railways, roads, transmission lines, and wind turbines. Increased avoidance behavior was predicted separately for selected habitat classes in combination with the mortality risk variables (Table 3).

The Advisory Team reviewed the range of values present in each source dataset and helped to define new categories and class breaks to prepare the data for the resistance modeling (see the 'Data Quality: Lineage' tab section in the FGDC metadata for the raster 'GSGCSageConOR2014_resistance'). The task of combining resistance values across the mortality risk variables and their subclasses was expedited through use of the Gnarly Landscape Utilities: Resistance and Habitat Calculator (McRae et al. 2013).

Each class of each dataset was assigned a relative resistance value (as the rounded average of recommendations from the Advisory Team) to represent its direct effect on sage-grouse movement through associated energy cost, difficulty of movement, and/or mortality risk. For variables believed to influence sage-grouse avoidance behavior, a separate resistance value to represent its indirect effect was then assigned to each class along with an avoidance distance, the distance from the disturbance within which the individual alters its behavior (Table 3). The relative resistance values for each dataset range linearly from 1 – 100, where 1 denotes ideal habitat and 100 represents heavily degraded habitat.

Resistance values associated with energy cost and movement difficulty are represented across the full analysis extent (Fig. 3), whereas those indicating mortality risk occur only where coincident with the physical footprints of mortality risk factors (Figs. 4). Resistance values representing avoidance behavior were applied: (a) using distance decay functions, (b) only to grid cells within the specified avoidance distance for each class, and (c) excluding grid cells with a mortality risk score (to avoid conflation of a feature's direct and indirect effects.)

Distance decay functions for avoidance factors differed by dataset type – densities were used with point and linear features, and inverse Euclidean distances were applied for raster classes. Density search radii and maximum Euclidean distances were set equal to avoidance distances such that both functions diminished to zero at the perimeter of each avoidance buffer. Resulting decay coefficients were masked to exclude grid cells with mortality risk scores, then multiplied by the resistance values assigned to avoidance factors to produce final avoidance resistances.

Once prepared, individual resistance inputs were summed first by resistance type for review, then summed again to form a single resistance surface with a value range of 1 - 268 (Fig. 5).

While most input datasets were prepared with full coverage across both the SageCon Assessment Area in Oregon and its 10-mile buffer (Fig. 1), a few datasets were discontinuous or absent within the buffer, including: the crop data layer, invasive annual grasses, tree canopy cover, and surface mining. Resulting edge effects outside of and along the Oregon state boundary may warrant lower confidence in interpretations made of model results outside the Oregon extent of the analysis area.

Table 1: Resistance Variables and Datasets

Variable	Resistance Type: Energy cost / Mvt difficulty	Resistance Type: Mortality risk	Resistance Type: Avoidance	Data type	Dataset(s)	Data model	Spatial extent
Habitat layer representing (inverse of) energy cost and movement difficulty							
Component datasets:							
Agriculture	X			Categorical	**National Landcover Dataset (NLCD 2011)**	Raster	SageCon Extended
				Categorical	**Crop Data Layer (National Agricultural Statistics Service, 2012)**	Raster	SageCon OR
Existing Vegetation Type	X			Categorical	**Ecological Systems (2012),** used in TNC's 2013 Columbia Plateau ecoregional update	Raster	SageCon Extended
Fire	X			Integer	**GeoMAC (2000 - 2012)**	Polygon	SageCon Extended
				Integer	**RSAC Burn Perimeters (1984 - 2000)**	Polygon	SageCon Extended
Invasives	X			Categorical	**ILAP 2013 (INR)**	Raster	SageCon OR
Tree canopy cover	X		X	Categorical	**Tree canopy cover (INR)**	Raster	SageCon OR
Feature physical footprints included as mortality risk factors							
Communication towers		X	X	Integer	**Communication towers (FCC)**	Point	SageCon Extended
Housing density *		X	X	Categorical	**Housing densities,** based on 2010 US census tracts with public lands removed	Raster	SageCon Extended
Mining (surface, active)		X	X	Categorical	**Mineral Information Layer for Oregon (DOGAMI)**	Point	SageCon OR
Pipelines (active)		X	X	Categorical	**NG pipelines (Ventyx 2014)**	Line	SageCon Extended
Power plants		X	X	Categorical	**Power plants (Ventyx, 2013)**	Point	SageCon Extended
Railways (active)		X	X	Categorical	**Railway network (FRA - USDOT, 2013)**	Line	SageCon Extended
Roads **		X	X	Categorical	**24k roads composite (BLM, TIGER, ODOT)**	Line	SageCon Extended
Transmission lines		X	X	Categorical	**Electrical transmission lines (Ventyx 2014)**	Line	SageCon Extended
Wind turbines		X	X	Integer	**Wind towers (Ventyx, 2014)**	Point	SageCon Extended

Densities and inverse Euclidean distances included as avoidance factors							
Selected classes from Habitat layer	X		X	Categorical	**National Landcover Dataset (NLCD 2011)**	Raster	SageCon Extended
Communication towers			X	Integer	**Communication towers (FCC)**	Point	SageCon Extended
Mining (surface, active)		X	X	Categorical	**Mineral Information Layer for Oregon (DOGAMI)**	Point	SageCon OR
Pipelines (active)		X	X	Categorical	**NG pipelines (Ventyx 2014)**	Line	SageCon Extended
Power plants		X	X	Categorical	**Power Plants (Ventyx, 2013)**	Point	SageCon Extended
Railways (active)		X	X	Categorical	**State Railway System linework (ODOT, 2009)**	Line	SageCon Extended
Roads **		X	X	Categorical	**24k roads composite (BLM, TIGER, ODOT)**	Line	SageCon Extended
Transmission lines		X	X	Categorical	**Electrical transmission lines (Ventyx 2014)**	Line	SageCon Extended
Tree canopy cover	X		X	Categorical	**Tree canopy cover (INR)**	Raster	SageCon OR
Wind turbines		X	X	Integer	**Wind towers (Ventyx, 2014)**	Point	SageCon Extended

** Housing density data were not processed separately as an avoidance factor because it was presumed its geometry – large polygons based in part on census tracts – would already encompass areas in which avoidance behavior might be expected.*
*** The 1:24,000 roads input was compiled between BLM GRTN data within Oregon and TIGER data in CA, NV, and ID. After removing duplicate features, road type and Annual Average Daily Traffic (AADT) volumes from ODOT were used in combination to define three classes of use level. 'High': Interstate OR AADT > 2500; ' Moderate': AADT <= 2500 OR US/State/Major Highways; 'Low': ROADTYPE = 'All other roads' classified independent of traffic flow data. Additionally and by BLM request, 'lightly-used' roads were removed from the input data. These included features in the BLM GRTN data that occurred outside of Wilderness Study Areas (WSAs) and for which any of the following criteria were true: (1) the road was unnamed; (2) Maintenance level < 3; (3) CartoRoad <> 'Intermediate' or 'Major'; (4) Drivability <> '2wdLow'; (5) NumLanes <> 'DL, 'ML', or 'MD'; (6) RoadClass <> 'Arterial' or 'Collector' or 'Local'; or (7) Surface <> 'Bituminous', 'Concrete', 'Aggregate', or 'PitRun'.*

Table 2: Development of Habitat Layer

Habitat Classification	Description
Dunes	Dunes (ESYST) where INR Tree canopy closure (CC) = 'Trace or less'
Playas	Playas (ESYST) where INR Tree CC = 'Trace or less'
Grasslands	Grassland (ESYST) where INR Tree CC = 'Trace or less' and ILAP exotic annual grass < 8%
Grasslands, with >= 8% exotics	Grassland (ESYST) where INR Tree CC = 'Trace or less' and ILAP exotic annual grass >= 8%
Sage-steppe - Basin	Sage-steppe (ESYST) where INR Tree CC = 'Trace or less'
Sage-steppe - Montane	Montane Sage (ESYST) where INR Tree CC = 'Trace or less'
Shrubland - Basin (excluding sage)	Basin Shrubland (ESYST) where INR Tree CC = 'Trace or less'
Shrubland - Montane	Montane Shrub (ESYST) where INR Tree CC = 'Trace or less'
Chaparral	Chaparral (ESYST) where INR Tree CC = 'Trace or less'
Savanna with < 4% CC (light)	Savanna (ESYST) where < 4% CC
Savanna with 4 - 10% CC (dense)	Savanna (ESYST) where 4 - 10% CC
Woodland and Forest (excluding Aspen)	Tree-dominated classes (ESYST) where INR Tree CC > 10%
Water	Lakes and ponds (NWI) or Open water (NLCD)
Emergent, herbaceous wetlands	Wet meadows (ESYST) or Wet meadow - unmanaged (Donnelly)
Wet Meadows	Wetlands (NWI) where INR Tree CC < 2 or Emergent herbaceous wetlands (NLCD)
Woody Wetlands	Woody wetlands (NLCD) or Wetlands (NWI) where INR Tree CC >= 2
Riparian	Riparian (Donnelly) or Riparian types (LF2010)
Aspen	Deciduous (NLCD) or Aspen (ESYST) or Aspen (LF 2010)
Pasture / Hay	Ag and Pasture (NLCD) and Pasture (CDL 2012)
'Selected' Agriculture (<500m from edge AND/OR important to sage-grouse per Donnelly data.)	Ag (NLCD) or Ag (CDL 2012) or Alfalfa (Donnelly)
'Avoided' Agriculture (>=500 from edge AND not identified in Donnelly data.)	Ag (NLCD) or Ag (CDL 2012) or Alfalfa (Donnelly)
Cliffs	Cliffs (ESYST)
Rocks, Barren, Lava	Lava, barren, alpine rock and scree, snow/ice (NLCD or ESYST)
Developed - Open space	Developed - Open space (NLCD)
Developed - Low intensity	Developed - Low intensity (NLCD)
Developed - Medium intensity	Developed - Medium intensity (NLCD)
Developed - High intensity	Developed - High intensity (NLCD)

Table 3: Resistance Value Assignments and Avoidance Distances (meters)

Variable	Classification	Resistance Values Assignments: Direct Effects (Energy cost, movement difficulty and/or mortality risk)	Resistance Values Assignments: Indirect Effect (Avoidance behavior)	Avoidance Distances (m)
Habitat	Dunes	1		
	Playas	1		
	Grasslands	1		
	Grasslands, with >= 8% exotics	5		
	Sage-steppe - Basin	0		
	Sage-steppe - Montane	0		
	Shrubland - Basin (excluding Sage-Steppe)	0		
	Shrubland - Montane	2		
	Chaparral	5	2	100
	Savanna with < 4% CC (light)	7	3	100
	Savanna with 4 - 10% CC (dense)	10	4	100
	Woodland and Forest (excluding Aspen)	16	6	100
	Open Water	5		
	Emergent, Herbaceous Wetlands	2		
	Wet Meadows	2		
	Woody Wetlands	8	3	100
	Riparian	2		
	Aspen	4	3	100
	Pasture / Hay	2		
	'Selected' Agriculture (<500m from edge AND/OR important to sage-grouse per P. Donnelly data.)	1		
	'Avoided' Agriculture (>=500 from edge AND not important to sage-grouse per P.Donnelly data.)	6		
	Cliffs	7		
	Rocks, Barren, Lava	7		
	Developed - Open space	1		

Table 3: Resistance Value Assignments and Avoidance Distances (meters) *(Continued)*

		Resistance Values Assignments		
Variable	**Classification**	**Direct Effects**	**Indirect Effect**	**Avoidance Distances (m)**
Habitat *(continued)*	Developed - Low intensity	13		
	Developed - Medium intensity	74		
	Developed - High intensity	99		
Communication towers	Shorter towers	5	4	1000
	Taller towers	7	5	2000
Housing density (Dwelling Units per Acre)	Residential - Rural low (0.001 - 0.006 DUA)	1		
	Residential - Rural (0.006 - 0.025 DUA)	6		
	Residential - Exurban low (0.025- 0.1 DUA)	13		
	Residential - Exurban (0.1- 0.4 DUA)	48		
	Residential - Low (0.4- 1.6 DUA)	74		
	Residential - Moderate (1.6 - 10 DUA)	83		
	Residential - High (> 10 DUA)	99		
Mining (surface, active)		89	50	3000
Pipelines (active)		3	1	30
Power plants		99	40	5000
Railways (active)		11	6	1000
Roads	High use	33	15	5000
	Moderate use	25	10	3000
	Low use	3	1	3000
Transmission lines	4 kV, one line	3	3	1000
	35 kV, one line	3	3	1000
	69 kV, one line	3	3	1000
	69 kV, two lines	6	7	2000
	115 kV, one line	4	3	1000
	138 kV, one line	4	3	1000
	230 kV, one line	7	8	2500
	230 kV, two lines	10	10	5000
	500 kV, one line	10	10	5000
Tree canopy cover	4 - 10 % cover	11	4	0
	> = 10% cover	26	9	120
Wind turbines		21	13	2000

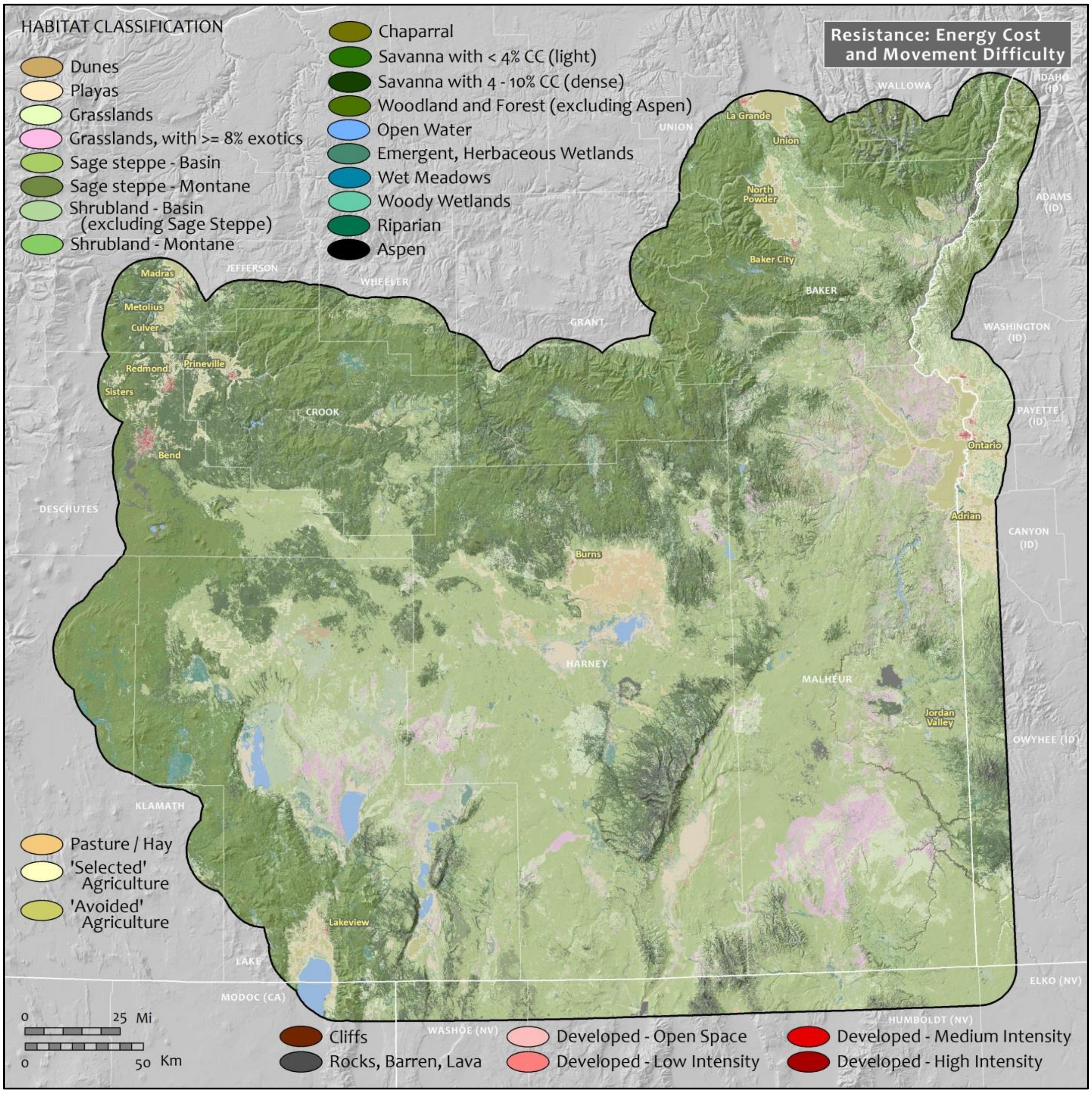

Figure 2: Habitat Classification

These classes were included in modeling of resistance due to energy cost and movement difficulty (see Figure 3).

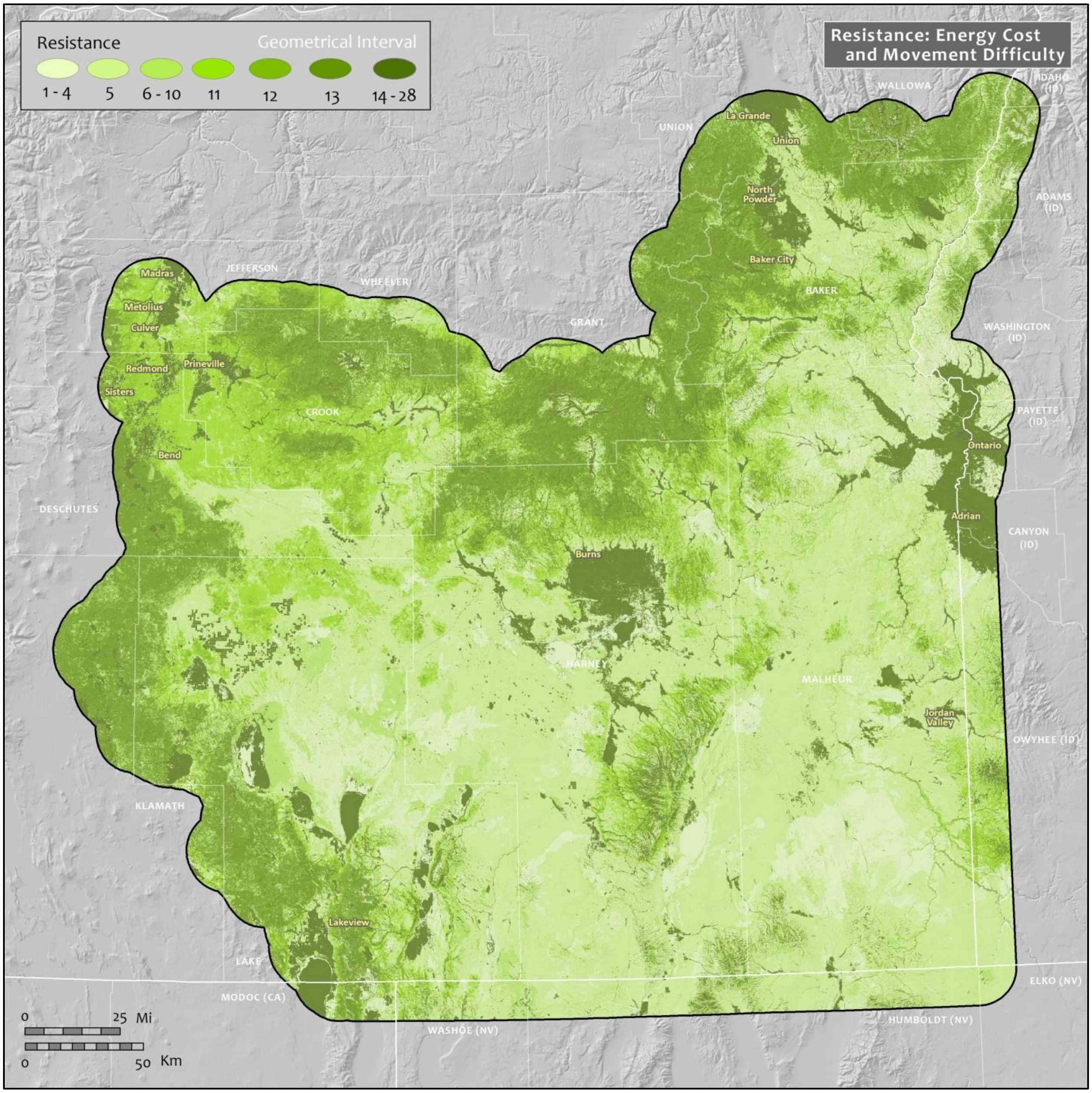

Figure 3: Resistance: Energy Cost and Movement Difficulty
Higher resistance values indicate greater cost and difficulty for sage-grouse movement. The geometrical interval classification algorithm ensures that a class range has approximately the same number of values in each class and that the change between intervals is relatively consistent.

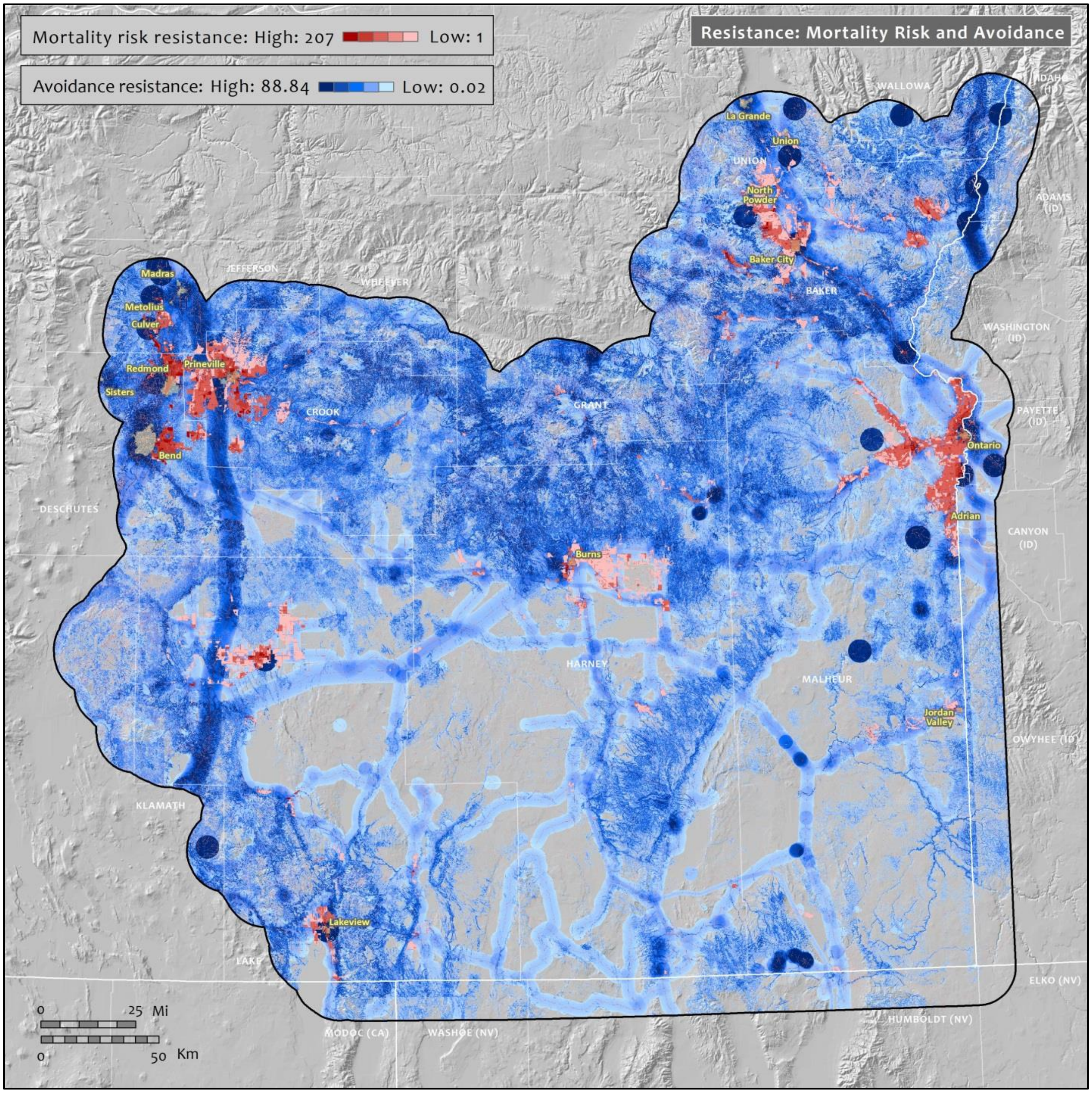

Figure 4: Resistance: Mortality Risk and Avoidance

Higher resistance values indicate greater mortality risk or resistance due to avoidance behavior. The highest mortality risk resistance values visible at this scale largely reflect high housing densities, whereas the highest visible avoidance resistance values are primarily associated with powerplants and high-voltage transmission lines.

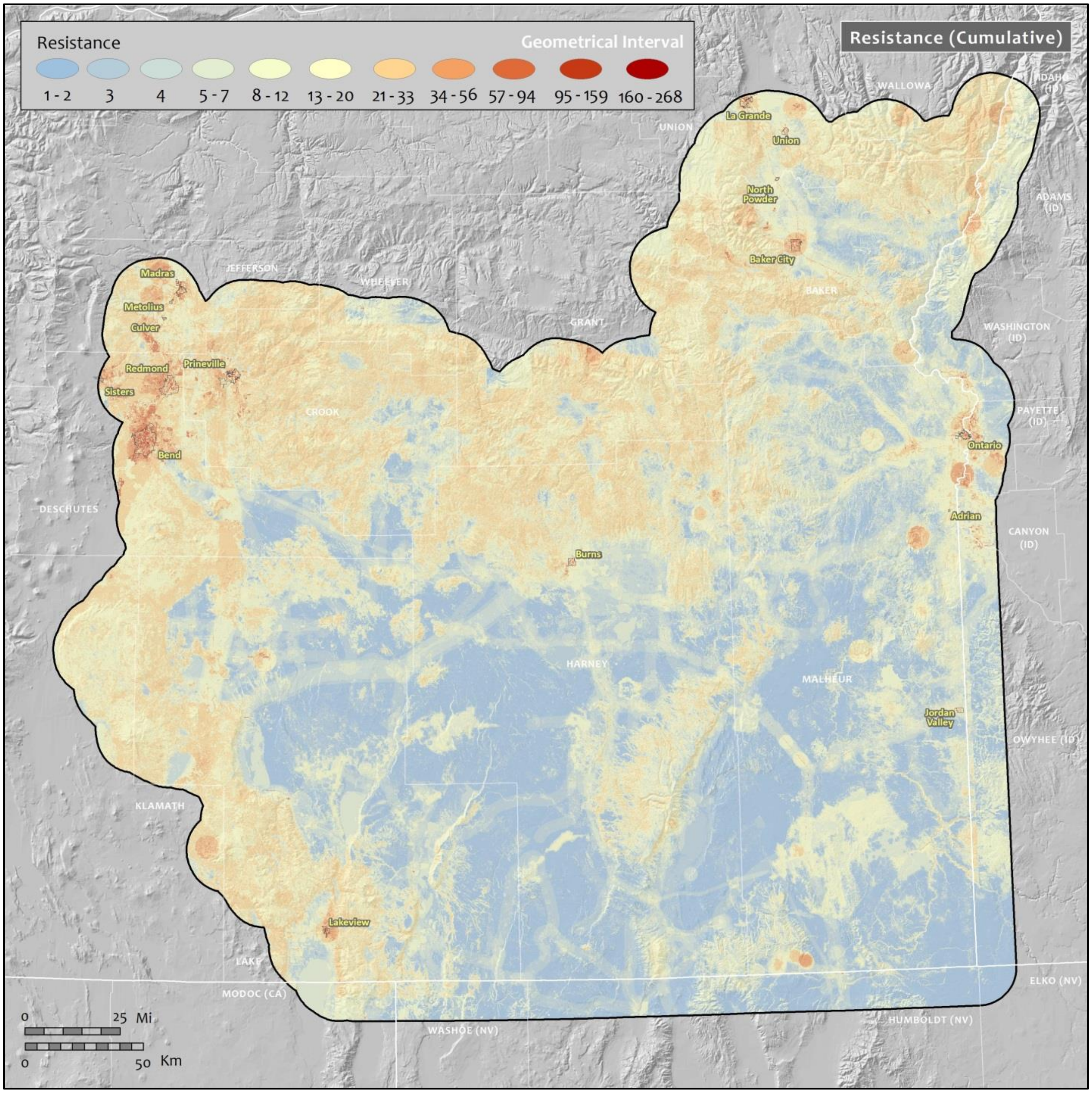

Figure 5: Resistance: Cumulative
Higher resistance values indicate greater cost and difficulty for sage-grouse movement, greater mortality risk, and/or greater avoidance behavior.

Lek Kernel Development

A *lek kernel* is an area surrounding a lek which is modeled as the area most accessible to a female sage-grouse moving outward from the lek in search of a suitable nesting site. These areas serve as both source and destination habitat patches between which habitat connectivity for sage-grouse movement was analyzed in conjunction with the related cost-weighted distance (CWD) surface, using the Linkage Mapper toolbox (McRae and Kavanagh 2011).

Lek kernels were seeded at each specified lek and grown using the resistant kernel algorithm as a function of the CAPS traversability metric, one of three metrics of potential functional connectivity described in Compton et al. (2007) and McGarigal et al. (2012). The algorithm, a hybrid approach between the standard kernel estimator and least-cost paths (LCPs), estimates the realized ecological neighborhood around each target cell (lek) as a GIS focal operation (neighborhood statistic) using a dispersal parameter (bandwidth, measured in meters as the standard deviation of the kernel), a cost (resistance) matrix, and a search distance (indicating the maximum spread of the kernel as a multiple of bandwidth). The bandwidth and search distance parameters were set to simulate a 5 km nesting movement distance – i.e. the distance from leks within which approximately 80% of sage-grouse nests were found to occur (Hagen 2011). Towards this goal, bandwidth was set to a value of 1705 and the search distance parameter to 3 so as to approximate (assuming a normal distribution) the desired radial kernel spread of 5 km. The resistance surface developed for sage-grouse across the SE Oregon study area served as the cost surface (Fig. 5).

Lek kernels were delineated for a target set of leks in the study area (Fig. 6). In Oregon, this comprised all leks within lek complexes in addition to those leks with a Conservation Status of ‘Occupied’, ‘Occupied pending’, ‘Unoccupied pending’, or ‘Unknown’. In areas of California, Nevada, and Idaho within the SageCon study area’s 10-mile buffer, all leks were included except those of ‘Historic’ (presently unoccupied) status.

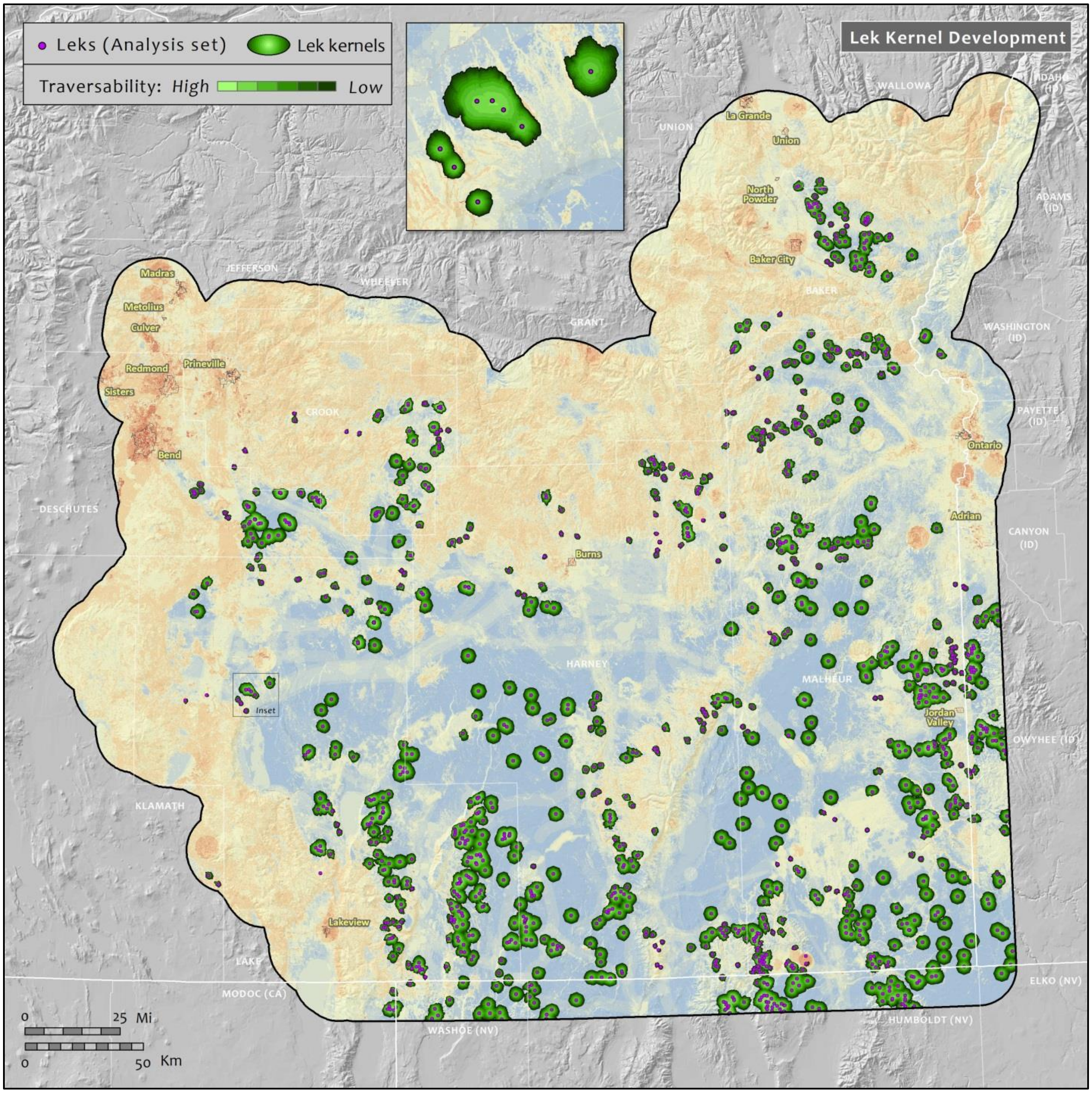

Figure 6: Lek Kernel Development
A kernel was seeded at each lek in the analysis set, then grown outward to represent the realized ecological neighborhood for a female sage-grouse moving outward from the lek. Typically, kernel spread is larger in areas of low resistance (see Inset).

Cost-weighted Distances (CWDs)

Cost-weighted Distances (CWDs) are geographic distances modified by resistance values to represent the *effective distances* for species movement in a study landscape. Operationally, the geographic or Euclidean distance associated with any two contiguous cells equates to the raster's cell size multiplied by 1 for orthogonal adjacencies or by 1.4142 (i.e., the square root of two) for diagonal adjacencies. The respective CWD is then calculated as this Euclidean distance multiplied by the average of resistance values between the two cells. The CWD between two non-contiguous cells, then, is simply the CWDs for each intervening pair of adjacent cells summed along the most direct route between the terminal cells. In a CWD surface, each cell value is the CWD to that cell from the nearest source area of species movement. The CWD surface for this analysis contains cell values of cost-weighted kilometers calculated outward from the lek kernels over the resistance surface (Fig. 7).

Instrumental to subsequent linkage modeling, the lek kernels and CWD surface also serve as a pair of key, self-standing data products with significant interpretive value. While the lek kernels characterize the traversability of local habitat surrounding leks, the CWD surface represents the relative isolation between the lek kernels and the relative difficulty of sage-grouse movement across the intervening landscape mosaic. The CWD surface further serves to complement the specificity of subsequent linkage maps with its "broad-brush" and wall-to-wall coverage of the study area. This characteristic perhaps best conveys: (1) the wide array of paths individual birds may select in progressively navigating the landscape, (2) spatial uncertainty stemming from the resolution of input factor data, and (3) uncertainty associated with how birds actually perceive and respond to resistance factors in the landscape (WHCWG 2010).

Least-cost Paths (LCPs)

Least-cost paths (LCPs) provide a measure of the structural connectivity, or *continuity*, of sage-grouse habitat amid the network of habitat patches defined by the lek kernels dataset. Each LCP identifies the single-cell wide (30 meter) route of least cumulative resistance for an individual sage-grouse moving between a given pair of adjacent lek kernels. LCPs were identified and mapped with the Linkage Mapper toolset (McRae and Kavanagh 2011) using the lek kernels data and the CWD surface (Fig. 7) as inputs.

In context of the broader analysis, LCPs serve both as discrete representations of linkages between adjacent pairs in the lek kernel network and as a conceptual basis for least-cost corridors. LCPs and corridors derive from the spatial configuration and continuity of habitat in the study landscape. While they depict modeled routes of least cumulative resistance, neither necessarily correlate with known routes of sage-grouse migration nor describe the likelihood of particular routes attempted by individuals. That being so, while modeled as connections between lek kernels, over a quarter of the linkages were found to also connect lek kernels to nearby late summer brood-rearing habitat as modeled by Donnely et al. (2014).

The least-cost approach to modeling connectivity serves to complement the study's circuit theoretic component in several respects. First, delineation of LCPs provides an intuitive and distinct visualization of the full analysis network. Second, metrics of linkage *quality* and *robustness* (combined in this study into a single metric – see 'Linkage Statistics') enable distinct comparison between linkages as represented by the LCPs. Third, corridors demarcate broad belts of land with relatively greater habitat continuity; such linkage zones are useful for framing potential conservation actions and for constraining models based in circuit theory (see 'Pinch-points' and 'Barriers and Restoration Opportunities Analysis').

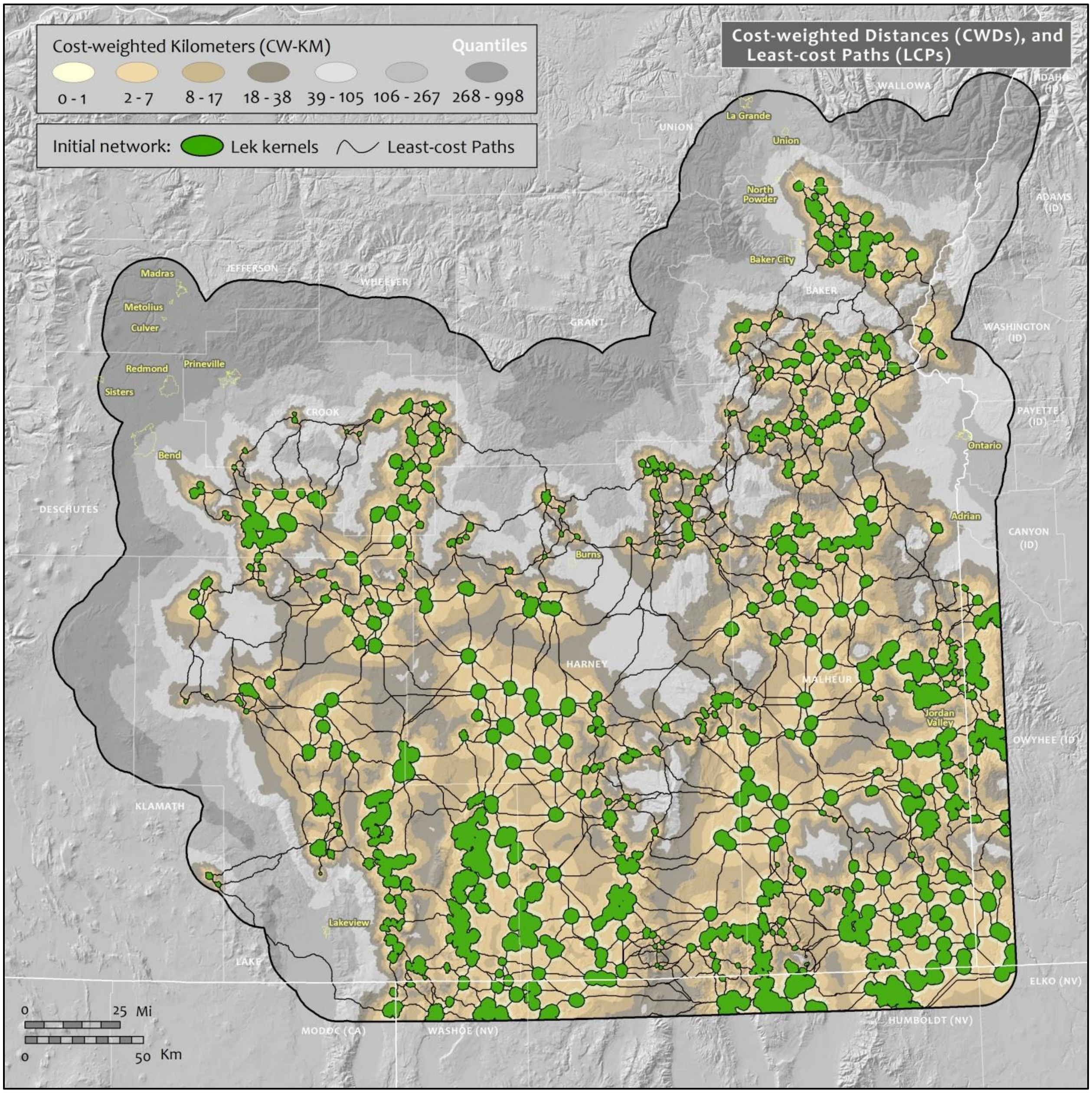

Figure 7: Cost-weighted Distances (CWDs) and Least-cost Paths (LCPs)
Sage-grouse traversal of the landscape between a given lek kernel pair is predicted as easier when intervening CWD values are consistently low, and more difficult where classes of higher CWD values occur.

Network Refinement

Using Linkage Mapper, a preliminary network of lek kernels (n = 362) was constructed in which linked kernel pairs were defined by adjacency in either Euclidean *or* cost-weighted space. Minimum accumulated CWDs were calculated between each lek kernel pair, and an LCP mapped for each linkage with the exclusion of those that would intersect an intermediate lek kernel (n = 964).

The initial analysis network of target lek kernels and associated LCPs resulted in a large set of linkage corridors with extensive overlap, making it difficult to proceed with analyses and interpretation. Consequently, a decision was made to further refine the network prior to continuing with the analyses.

With guidance from the Advisory Team, a ruleset was devised to hone the lek kernel network to remove potential linkages of relatively low importance and facilitate interpretation of the remaining individual linkage zones (Fig. 8).

Network refinement began with the application of an appropriate threshold CWD value over which LCPs would be removed; this threshold was determined through iterative modification of maximum CWD values with visual review of the resulting networks. Based on the Advisory Team's recommendations, all LCPs of > 120 cw-km were removed with the exception of three required to maintain a minimum of two linkages for every lek kernel (n = 54); this latter "path redundancy rule" was adopted so as to support analysis of at least one alternative movement route with the effective loss of any linkage to fire or other disturbance event. Second, a few linkages (n = 3) were reinstated into the analysis set.

Next, network constellations determined to be presently well-connected were removed from the full analysis network. These linkages (n = 647) and associated lek kernels (n = 149) were first classified as either *internal* or *external*. Internal linkages (n = 426) were defined as those connecting two lek kernels *within* the same core area or BBD area, and internal lek kernels (n = 122) defined as those connected only by internal linkages. External linkages (n = 221) were defined as those both < 90 cw-km and < 11.3 (Euclidean) km in length, the latter equal to the mean plus one standard deviation of straight line distances (km) measured edge-to-edge between all lek kernel pairs within any single core area. The associated external lek kernels (n = 27) were defined as those connected only by internal linkages *and/or* linkages < 90 cw-km and < 11.3 km.

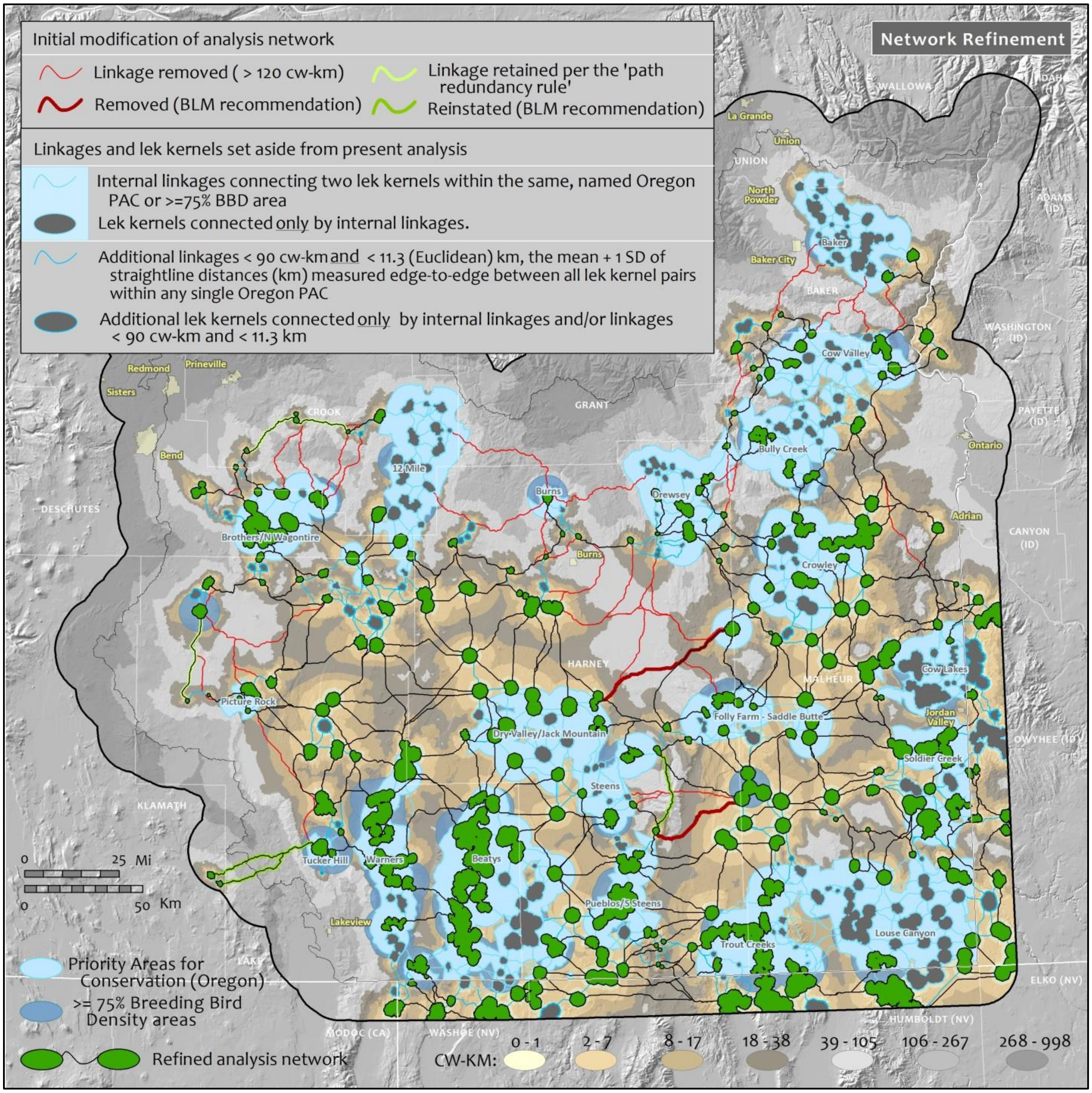

Figure 8: Network Refinement

In sum, 54 linkages were removed during the initial modification of the analysis network. 647 linkages and 149 lek kernels were then set aside in the assumption of their being presently well-connected for unrestricted sage-grouse movement. The refined analysis network then comprised the remaining 263 linkages and 213 lek kernels.

Linkage Statistics

To better inform comparisons between linkages in the refined analysis network (263 LCPs and 213 lek kernels) for conservation planning, statistics for each linkage were used to derive two linkage metrics and, in turn, a single composite linkage index.

The first metric, a measure of *linkage quality*, was based on the *inverse* of the *CWD to Path Length Ratio*, the total cumulative cost along an LCP divided by the Euclidean distance along the same path. This statistic, independent of LCP length, is a measure of the average resistance encountered along an LCP (Eq. 1).

$$\mathit{Unstandardized\ linkage\ quality}$$

$$x = Max\left(\frac{CWD\ along\ LCP}{Euclidean\ distance\ along\ LCP}\right) - \left(\frac{CWD\ along\ LCP}{Euclidean\ distance\ along\ LCP}\right) \qquad \text{(Eq. 1)}$$

The second metric, interpreted as a measure of *linkage robustness*, stems from the *CWD to Effective Resistance Ratio*. The *effective resistance* statistic, calculated using Circuitscape within defined linkage zones, serves as a measure of the relative isolation of lek kernels that accounts for the availability of multiple movement routes. The CWD to Effective Resistance Ratio, in turn, can be understood as a measure of average corridor width, the availability of multiple, low-resistance routes within a corridor, and – by extension – the robustness of the linkage to being severed (Eq. 2).

$$\mathit{Unstandardized\ linkage\ robustness}$$

$$y = \frac{CWD\ along\ LCP}{Effective\ resistance} \qquad \text{(Eq. 2)}$$

Raw statistic values from LCPs were standardized from 0 – 1 to constitute each linkage metric and the metrics then multiplied to produce the *linkage index* (Eq. 3).

$$Linkage\ index = \left(\frac{x - min(x\ across\ network)}{\max(x\ across\ network) - \min(x\ across\ network)}\right)\left(\frac{y - min(y\ across\ network)}{\max(y\ across\ network) - \min(y\ across\ network)}\right) \qquad \text{(Eq. 3)}$$

Although the linkage index derives from one statistic defined at the extent of single-cell wide LCPs and a second statistic defined across the full breadth of linkage zones, the index itself was mapped to the LCPs for the sake of greater visual clarity when superimposed over raster model outputs (Figure 6.1).

The result serves as an integrated measure of linkage quality and average corridor width, with higher values suggestive of areas warranting greater linkage protection (also see 'Discussion').

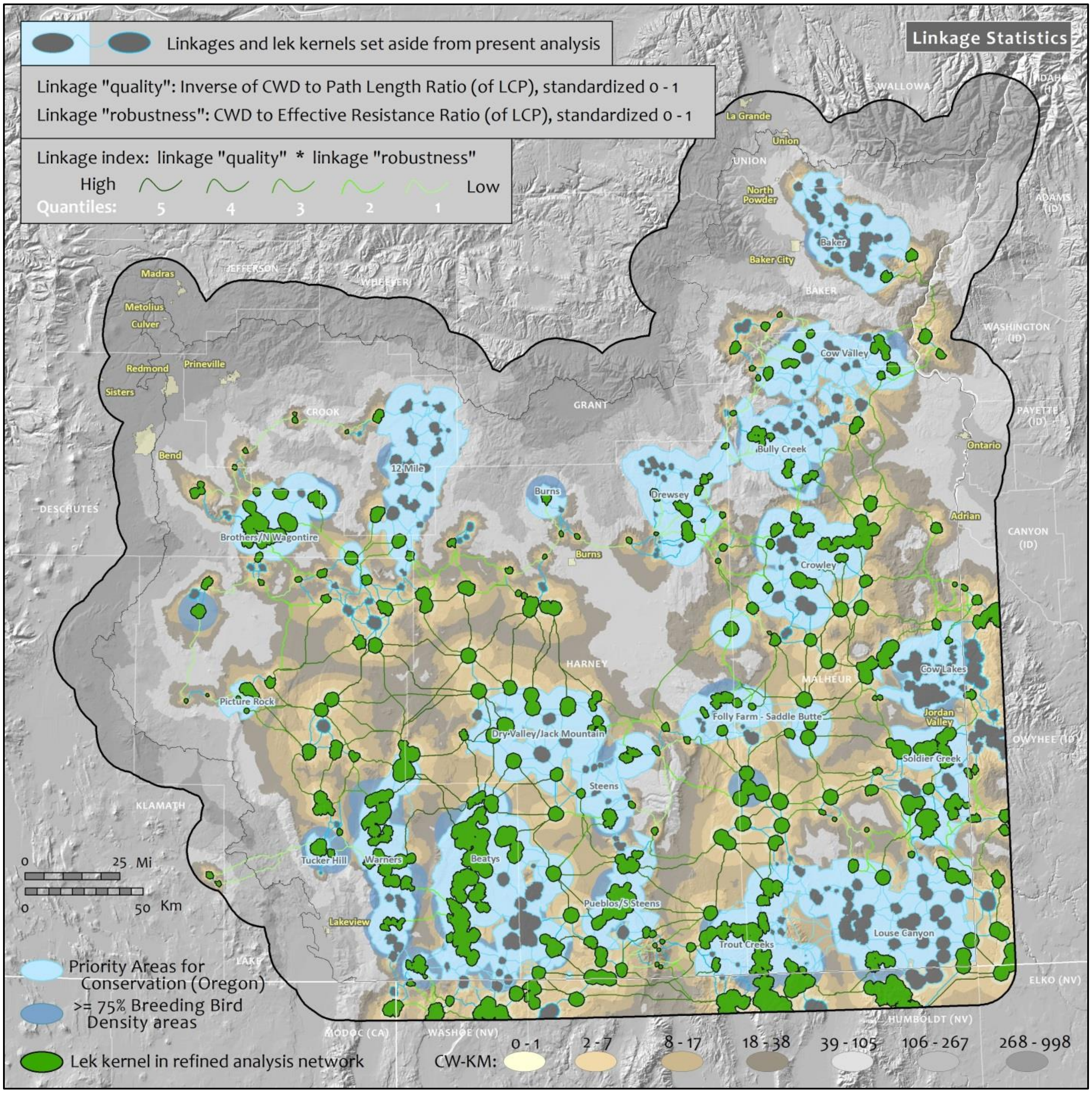

Figure 9: Linkage Statistics

Normalized Least-cost Corridors (NLCCs)

With a refined analysis network established and linkage metrics calculated, a normalized least-cost corridor (NLCC) surface was produced as follows. First, for each linkage (n = 263), a least-cost corridor was calculated as the sum of the two CWDs for the respective lek kernel pair, where resulting cell values represent the deviation in cumulative CWD values from the associated LCP. Each "raw" corridor was then normalized by subtracting the cost distance of its associated LCP. Lastly, NLCCs were narrowed to areas most relevant to conservation planning by applying a maximum cutoff width to restrict corridor widths. Three alternative maximum cost-distance values of 20, 10, and 5 cw-km were tested; of these, the 10 cw-km cutoff value was selected for further analyses as it resulted in reasonably narrow corridor widths without the loss of alternate, redundant branches in several linkage zones.

Once normalized, these corridors of variable habitat quality are depicted on the same scale (Fig. 10). Nevertheless, comparisons based on several corridor characteristics can provide insights to complement the linkage index. First, relative corridor width (Euclidean) reflects the number of alternative routes through similar quality habitat (with wide linkages typically indicative of more potential pathways through higher-quality habitat). Note that linkage width has no correlation with the actual area required to conserve linkage connectivity (WHCWG 2010). Second, the presence of secondary corridors within a given linkage may support more valuable path redundancy over alternate routes within a single corridor. Third, attention should be given to the spatial configuration of corridors, including their relative isolation or contiguity. Fourth, one may note the curve of increasing normalized CWDs measured cross-wise to a linkage; wide areas in low cost-weighted kilometers (warm hues in Fig. 10) suggest more resilient structural connectivity, whereas diffuse areas in high cost-weighted kilometers (cool hues) indicate more marginal or tenuous habitat continuity.

Pinch-point Analysis

Utilizing the Pinch-point Mapper tool (McRae 2012b) in the Linkage Mapper toolkit, Circuitscape was implemented to identify *pinch-points*, areas where connectivity could be severed with the loss of a relatively small amount of dispersal habitat (Fig. 11).

For each linkage, a hypothetical electric current was applied between the associated pair of lek kernels. The current was run over squared resistance values to increase contrast in the resistance raster, and flow for each linkage zone was limited to areas below the same CWD threshold (10 cw-km) used to map the NLCCs. Locations of highly constricted and thus strong current flow are identified as pinch-points (warm hues in Fig. 11). Given the lower incidence or absence of alternative movement routes around such bottlenecks, habitat degradation and/or loss within them will, by unit area affected, entail a disproportionate adverse effect on connectivity. At a landscape scale, pinch-points are the areas at which linkages are most susceptible to being severed and which may deserve prioritization for habitat protection.

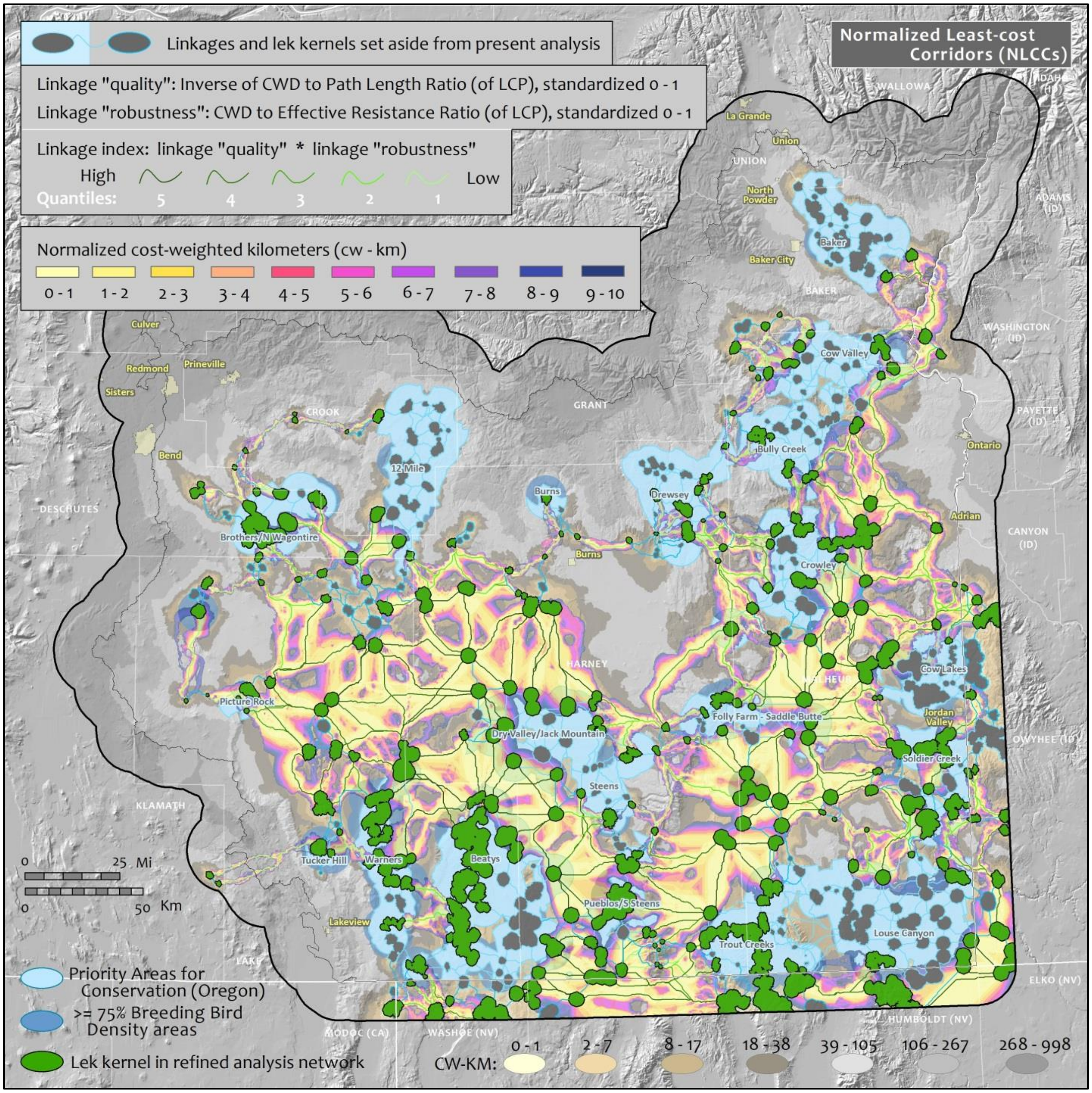

Figure 10: Normalized Least-cost Corridors (NLCCs)
Wide areas in low cost-weighted kilometers (warm hues) suggest more resilient structural connectivity, whereas diffuse areas in high cost-weighted kilometers (cool hues) indicate more marginal or tenuous habitat continuity. Linkage zones are defined by the extent of each NLCC.

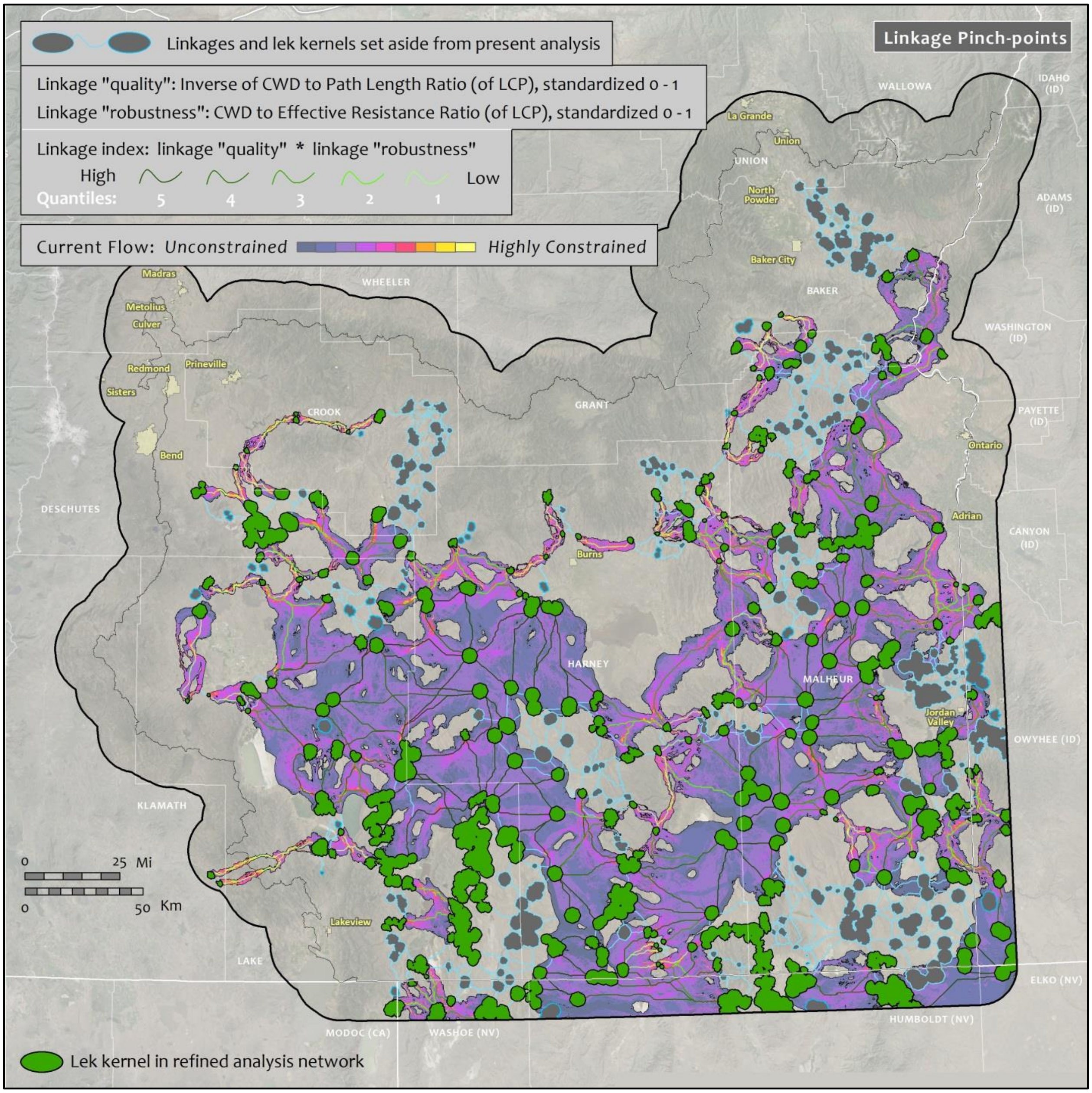

Figure 11: Linkage Pinch-points

Barriers and Restoration Opportunities Analysis

We used barriers analysis to locate areas within established linkage zones that exhibit the highest impact in reducing habitat continuity and where habitat restoration may lead to the greatest improvement in structural connectivity among spatially coincident linkages.

The analysis was conducted using the Barrier Mapper tool (McRae 2012a) in the Linkage Mapper toolkit. The approach derives barrier impact or restoration improvement scores for a linkage by estimating reductions in its least-cost distance (LCD), the lowest cumulative movement cost between the respective lek kernel pair. The tool iteratively progresses across the surface in a *moving window analysis*, calculating the LCD for each focal cell that would result if the resistance values within the window were set to 1.0 to represent full habitat restoration. For each focal cell, the difference between LCDs with and without restoration is then normalized by the neighborhood's diameter to yield a single metric of structural connectivity improvement per unit distance restored (McRae et al. 2012). Results are then combined over the study area, with each cell value set to the maximum (or sum) of barrier impact (or, restoration improvement) scores as taken across all lek kernel pairs; in this analysis, the barriers surface was mosaicked using maximum scores. At mid to fine-scales, the resulting surface may be used in conjunction with mapped pinch-points to assess relative conservation benefits between habitat restoration and protection (Fig. 12).

Note that size of the selected circular search neighborhood should correspond with that of the effective barrier one wishes to detect; in this case, a detection radius of 360-meter was chosen as a moderate size reasonably correlated with the effects of more diffuse habitat restoration strategies such as conifer removal.

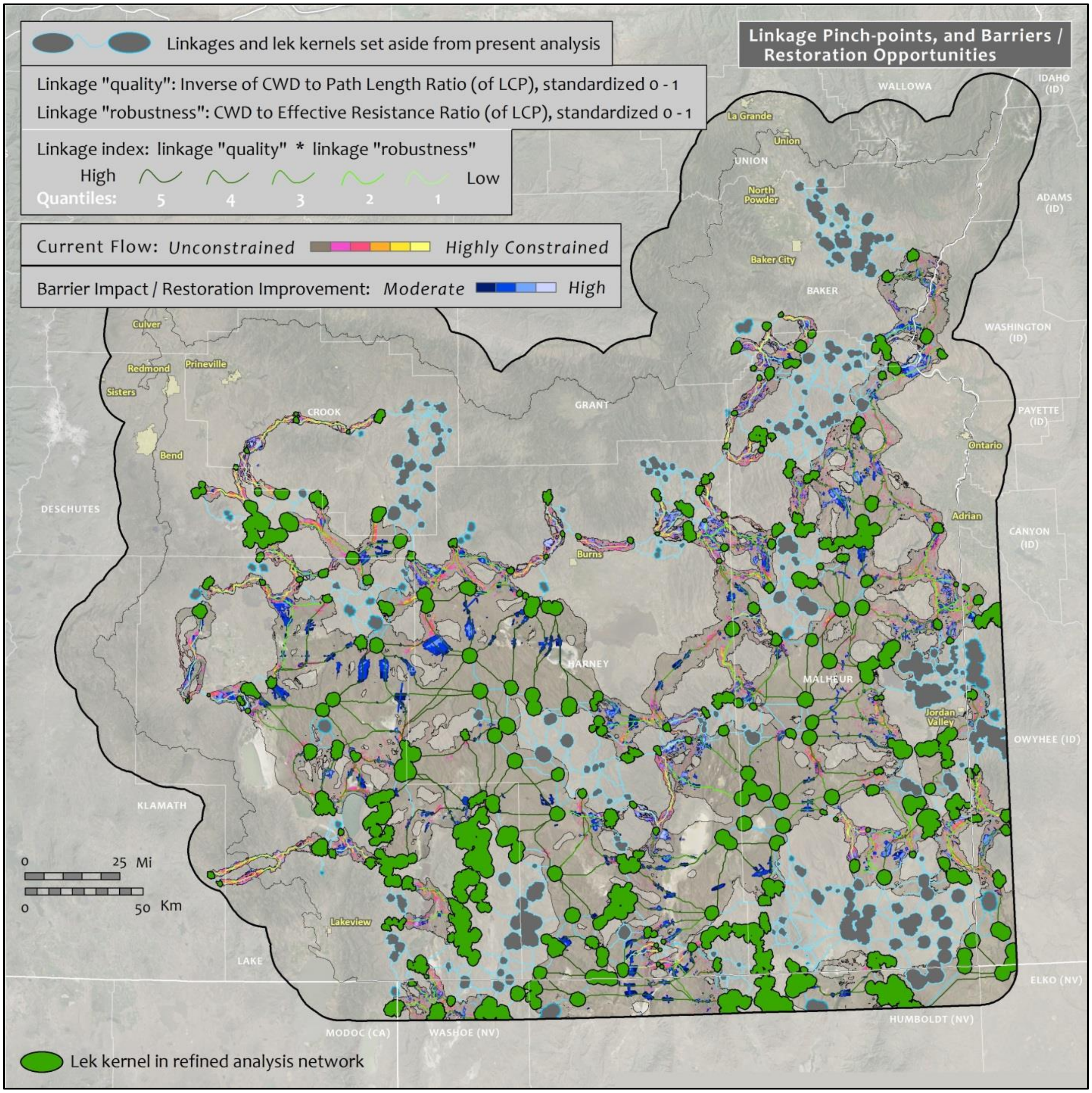

Figure 12: Barriers / Restoration Opportunities

DISCUSSION

Our main objective with this study was to provide and describe spatial data products helpful to informing priorities in the protection and/or restoration of sage-grouse dispersal habitat in southeast Oregon. Behind these products, the modeling of habitat connectivity involves assumptions regarding species movement capabilities, selection of dispersal habitat, mortality risks, and avoidance behavior. In our case, limited field data were available to characterize these aspects of sage-grouse movement ecology and to help guide model parameterization and calibration. In light of this challenge, we have developed results utilizing the best available spatial data on habitat variables across the study extent in combination with the professional judgment of our Advisory Team in guiding decision points through the modeling process. The results are provisional and should be further evaluated and validated with empirical data, including telemetry.

Habitat connectivity modeling is a specialized and technical endeavor. For our methods and results to be appropriately vetted (and perhaps emulated), it was necessary to use the concepts and terminology that are specific to the field (also see 'Glossary'). We have attempted to provide clear explanations for the methods and concepts for those seeking technical details. However, for a majority of readers, recommendations for use of the results to inform management are most important. Therefore, we offer guidance hereinafter on use of the study's spatial data products.

The small-format map reproductions in this document are intended primarily as illustrations to explain concepts and outline our modeling methods rather than as media to directly inform management decisions. While engaged in decision-making processes, land managers can benefit from the use of large-format maps; these may include large plots of map images in this report (particularly Figs. 9, 11 and 12 – available from the authors) and/or large maps constructed on-the-fly from the report's companion GIS content (see 'Data Products'). The latter may be most informative during review of potential management actions, as fine-scale mapping can focus on specific areas of interest in the study geography with display of additional reference features and/or recent imagery (such as available as a "basemap" from ArcGIS Online).

Users of the GIS data should note that GIS layer files have been included for quick compilation of such maps; adding these files to a map document in ArcGIS will reference data in the geodatabase and display them with prescribed classifications and symbology. The most pertinent layer files for customized, fine-scale maps are: 'AnalysisNetwork_LekKernels.lyr', 'LinkageStatistics_LinkageIndex.lyr', 'Pinchpoints.lyr', and 'Barriers.lyr'. Following is a recap of key points for their intepretation.

Lek kernels are models of the realized ecological neighborhoods for female sage-grouse moving outward from leks. The relative size of lek kernels provides land managers a readily interpretable indicator of the quality of dispersal habitat surrounding each lek. Larger kernels (or conjoined kernel clusters) indicate there are few structural impacts – such as juniper or man-made structures – to nesting or brood-rearing habitat. As the kernels are reduced in size, the quality of dispersal habitat is proportionally impaired (Fig. 13).

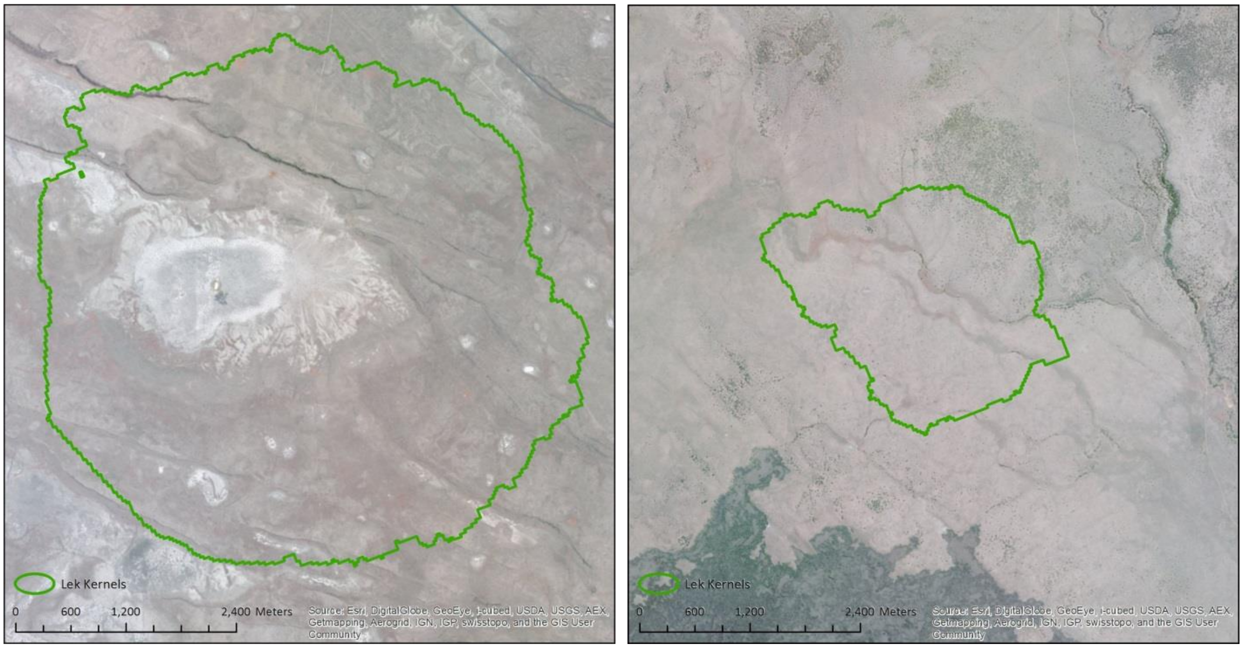

Figure 13: Comparison of Lek Kernel Size
The left image shows a larger lek kernel in a highly permeable landscape with few impediments to sage-grouse movement. On the right is a smaller kernel which has become constrained by conifer encroachment, primarily from the east, and a recent burn to the southwest (dark green).

Pinch-points represent areas of movement habitat that are in relatively good condition and where no comparable alternate paths exist. Higher scores indicate greater importance to network connectivity. In many cases, these are places that, if degraded or lost, could result in severed connectivity between one or more lek kernels. These areas are the most important to protect from development and habitat degradation.

Fine-scale inspection of the barriers data can help inform potential restoration activities. As the barrier impact score increases, so does the potential improvement to connectivity if the barrier were removed. Note that improvement to network connectivity through removal of a high impact barrier may not be limited to a single linkage zone; rather, the removal may result in the emergence of a new LCP and/or multiple, alternate lower cost paths. Either way, the result is a landscape more conducive to sage-grouse movement.

A barrier may be associated with the *direct* and/or *indirect effects* of natural features (e.g., juniper or other conifers) and/or anthropogenic obstructions (e.g., powerlines). In some cases (particularly with powerplants), an anthropogenic feature's indirect effects (i.e. those affecting avoidance behavior) may be predominantly responsible for increasing barrier impact scores. In these instances, the scope of the respective avoidance buffer can often be identified within the resistance surface ('GSGCSageConOR2014_Resistance') for consideration during planning.

At mid to fine-scales at which restoration projects are planned, pinch-points and barriers may be laid over imagery to help assess relative conservation benefits between habitat protection and restoration. Figures 14 and 15 focus on linkage zones between Jackass and Steens Mountains, including the confluence of the Donner und Blitzen River and Kiger Creek. Target leks in the area include: the Ham Brown Lake complex, Irish Lake, the Jack Mountain and Jack Mountain Burn complex, Little Kiger, the North Bridge Creek complex, and South Bridge Creek.

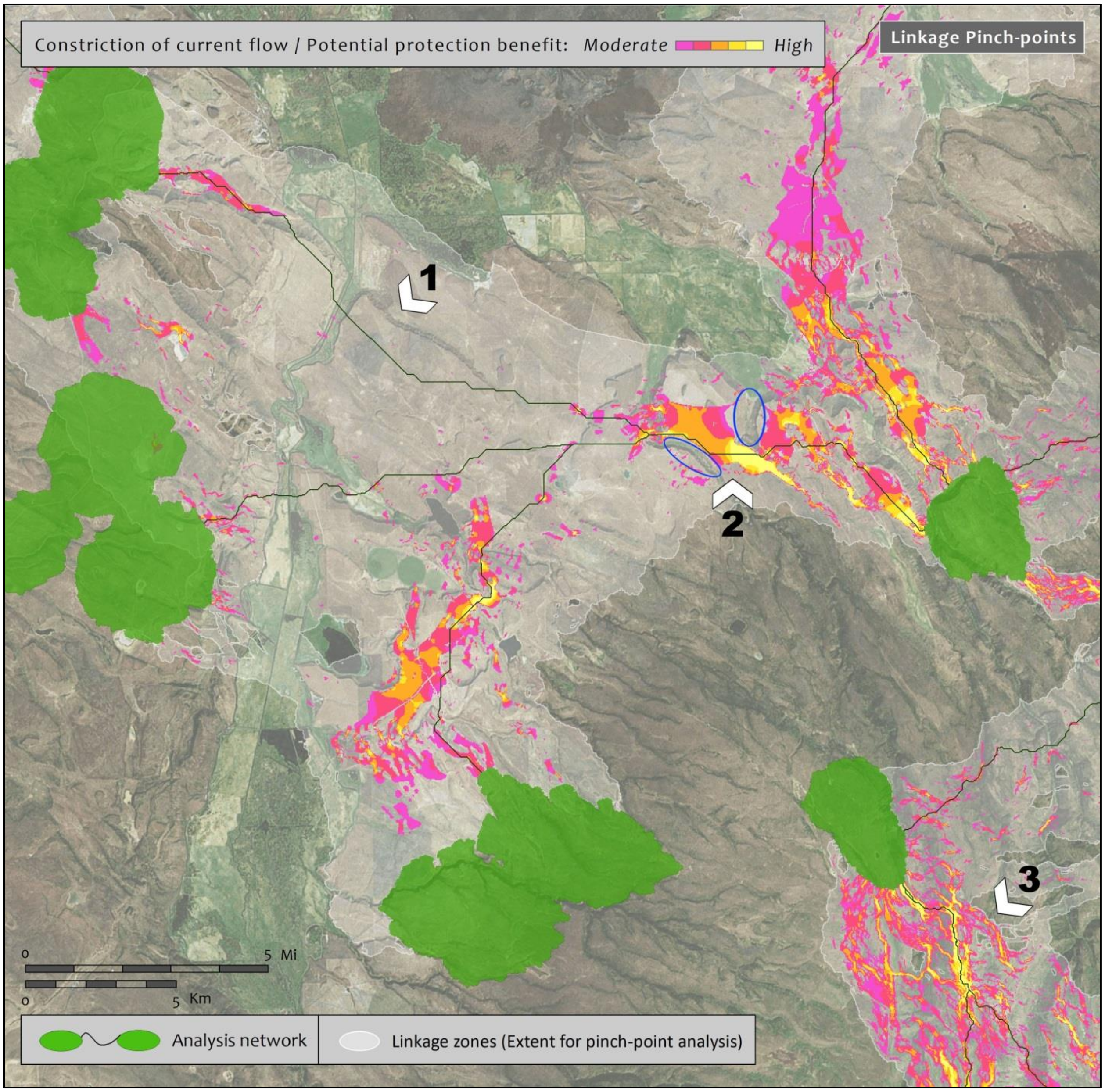

Figure 14: Pinch-points and Imagery Overlay
Location 1: Within the linkage zone, broad swaths without pinch-points reflect an area of homogenous habitat quality, diffuse current flow, and relatively low potential benefit from protective conservation actions.
Location 2 marks a distinct pinch-point. Note the two small adjacent patches to its south and east (blue ellipses). These correspond with distinct changes in topography and landcover -- including a deep channelization of Kiger Creek –features of high resistance that appear to funnel the current flow through the bottleneck. Loss of movement habitat in this pinch-point would likely severe connectivity to the three, converging linkage zones to its west; thus, network connectivity is likely to benefit highly from its protection (if viable).
Location 3: Current flow across this linkage is constrained through many small, braided stretches. Protection of movement habitat here may be less actionable here than at *location 2*.

In addition to further evaluation and validation at fine scales, we generally recommend that the data products from this study be used in conjunction with additional information when prioritizing restoration and protection activities. For this reason, pinch-points and barriers have been incorporated into the Oregon Rangeland

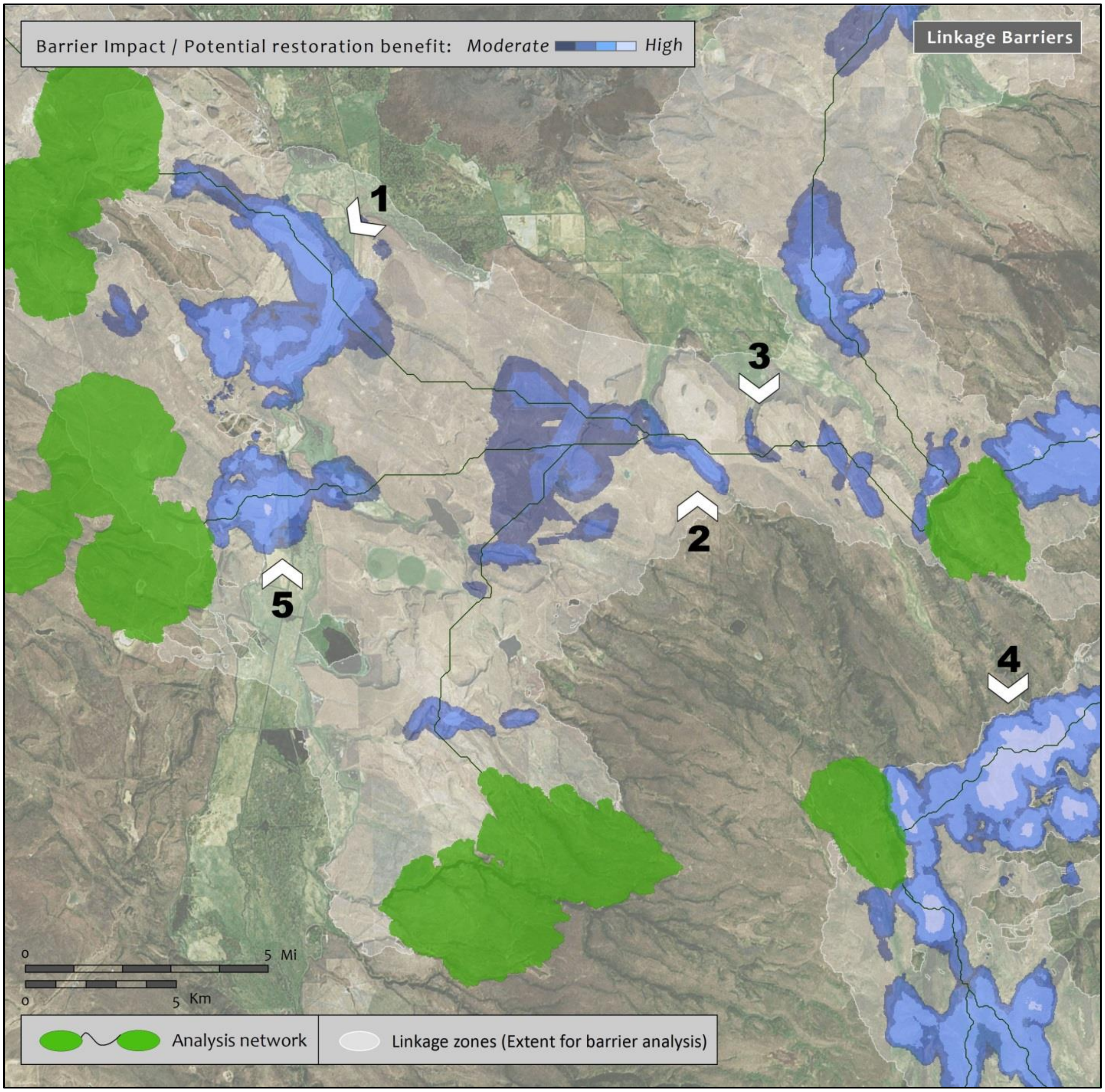

Figure 15: Barrier and Imagery Overlay
Locations 1, 2,** and **3: Barriers detected at these locations may not be actionable, as they largely correspond to high gradient channels and riparian vegetation along Dunner Und Blitzen River and Kiger Creek. Note also that the barriers at *locations* **2** and ***3*** roughly coincide with the features (blue ellipses in Fig. 14) on either side of a distinct pinch-point.
Locations 4** and **5: Juniper treatments at *location* ***4*** would result in a disproportionally large improvement to network connectivity. Such restoration may also be more actionable than addressing a barrier in agricultural lands that include a highway (*location* **5**).

Decision Support System (ORDSS), an initiative of TNC and INR which contains a wide variety of habitat and landuse metrics with relevance to the management of sage-grouse. All data within the ORDSS have been summarized to 640 acre (1 square mile) hexagons. In this case, the maximum values from the pinch-point and barrier datasets were attributed to each hexagon. This provides planners with additional context while making decisions on where to focus restoration efforts, allow development, etc.

ACRONYMS

BBD	Areas of >= 75% Breeding Bird Densities (Doherty et al. 2010)
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
CAPS	Conservation Assessment and Prioritization System (Compton 2014)
CWD	Cost-weighted Distance
DOGAMI	Oregon Deptment of Geology and Mineral Industries
DSL	Department of State Lands
ESYST	USGS ReGAP 2010, Terrestrial Ecological Systems
FCC	Federal Communications Commission
FRA-USDOT	Federal Railroad Administration, US Department of Transportation
GeoMAC	Geospatial Multi-Agency Coordination, US Geologic Service
IDFG	Idaho Department of Fish and Game
ILAP	Integrated Landscape Assessment Project, Institute for Natural Resources
INR	Institute for Natural Resources, Oregon University System
LCD	Least-cost Distance
LCP	Least-cost Path
LF 2010	LANDFIRE Existing Vegetation, circa 2010
NLCC	Normalized Least-cost Corridor (McRae and Kavanagh 2011)
NLCD	National Landcover Dataset, circa 2011
NWI	National Wetlands Inventory, USFWS
NWR	National Wildlife Refuge
ODFW	Oregon Department of Fish and Wildlife
ODOT	Oregon Department of Transportation
ORDSS	Oregon Rangeland Decision Support System
PAC	Priority Areas for Conservation (USFWS 2013)
RSAC	Remote Sensing Applications Center, US Forest Service
SageCon	Oregon's Sage-Grouse Conservation Partnership
TNC	The Nature Conservancy
USFS	US Forest Service
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey
WSA	Wilderness Study Area
WDFW	Washington Department of Fish and Wildlife

GLOSSARY

Actual functional (habitat) connectivity -- habitat connectivity modeled using field data on the actual movements of individuals (Fagen and Calabrese 2006). Also see potential functional (habitat) connectivity.

Analysis network – the specified network across which connectivity analyses are conducted. This network contains nodes – the locations that will be connected to each other (lek kernels), and the linkages (also: edges, or "links") that connect them.

Avoidance – the behavioral response of an organism to avoid a landscape feature due to indirect impacts such as noise, visual obstruction, and perceived threat.

Bandwidth – a parameter used in the resistant kernel algorithm developed by Compton et al. (2007). Measured as the standard deviation of the resistant kernel (in meters), bandwidth represents the maximum expected migration or dispersal distance an organism might traverse from a focal cell. The parameter determines which cells can be connected to a focal cell as least-cost paths are calculated between the focal cell and all other cells within its neighborhood.

Barriers - areas within established least-cost linkages that exhibit the highest impact in reducing habitat continuity and where habitat restoration may lead to the greatest improvement in structural connectivity among spatially coincident linkages. In some cases, barrier removal can allow new least-cost linkages to emerge, and/or create alternate lower cost paths.

Categorical data – a statistical data type that has multiple categories with no intrinsic ordering. Examples include hair-color, gender, dog breeds, etc.

Circuit theory – a branch of graph theory with a lexicon and algorithms specific to analysis of electrical circuit topologies. Algorithms from circuit theory can be used to model habitat connectivity across landscape mosaics. With the study landscape represented as a conductive surface, metrics including 'effective resistance', current flow, and voltage can be calculated to represent ecological processes such as individual species movement or gene flow across a metapopulation. In kind with graph theory more broadly, the circuit theoretic framework supports concurrent analysis of not only multiple but all possible species movement routes across a landscape (McRae et al. 2008).

Conceptual model – All GIS models operate upon mathematical abstractions of real-world concepts and entities. For species habitat connectivity modeling, the conceptual model must include nodes and linkages (see Analysis network) as well a resistance surface representing the ability and/or willingness of a species to traverse each cell of the modeled landscape mosaic when moving between nodes.

Connectivity – see habitat connectivity, structural connectivity, functional connectivity, potential connectivity, and/or actual connectivity.

Continuity – refers to the structural connectivity of habitat across the landscape. Continuity is affected by both the amount and configuration of habitat.

Core area – Areas defined by wildlife agencies as critical to the recovery of greater sage-grouse. Also known as 'Priority Areas for Conservation' and 'Preliminary Priority Habitat'.

Cost-weighted Distance (CWD; also, cost distance or effective distance) – a distance between points that incorporates the difficulty of moving between them. In a GIS, costs to movement are represented by a resistance surface. The CWD surface in this study is a measure of the relative isolation between lek kernels and the relative difficulty of sage-grouse movement across the intervening landscape mosaic.

Cumulative resistance – the total cost, calculated as the sum of all resistance values for all cells traversed between a source and destination node. The route between the source and destination nodes with the least cumulative resistance is the least-cost path.

Data model – in ArcGIS, a data model refers to the spatial representations (e.g. point, line, polygon, raster) of the themes (e.g. roads, transmission lines, land uses, etc.) used in a modelling exercise. A data model can also include the attributes of each theme and relationships amongst themes.

Density – the amount of an entity per unit area. In this analysis, density was calculated as a focal function, measuring the amounts of linear and point features within the search radius of a focal cell.

Destination – in connectivity analyses, a location that represents a 'to' node to be connected to a 'from' node (or source).

Direct effect – the energetic costs associated with the movement of a focal species through a particular land use or habitat type. The direct effect increases as the habitat suitability for the species decreases, potentially culminating in the demise of an individual (mortality risk).

Distance decay – a function that decreases in value as distance increases. Inverse Euclidean distance is a type of decay function.

Ecological System – a level of the U.S. National Vegetation Classification that groups plant associations into midscale units that are suitable for classification and mapping at scales relevant to many conservation applications.

Effective distance (also, cost distance or Cost-weighted Distance) **–** an ecological concept by which distance is defined in terms of the costs associated with movement of a focal species.

Effective resistance – calculated using Circuitscape within linkage zones. This serves as a measure of the relative isolation of lek kernels that accounts for the availability of multiple movement routes.

Empirical data – data that is the result of direct observation. In this case, telemetry data is one of the only empirical data sources that can inform connectivity modeling for sage-grouse.

Focal operation – the computation of an output raster where the output value at each cell location is a function of the value at that cell location and the values of the cells within a specified neighborhood around the cell. Focal operations are examples of *moving window* analyses.

Functional connectivity – a landscape's facilitation of ecological flows (including species movement). Functional *habitat* connectivity refers to the interaction of species movement with landscape composition and spatial configuration. Modeling functional habitat connectivity characterizes how individuals of a species may progressively perceive, interact with, and move through the landscape mosaic (Jones 2004; Crooks and Sanjayan 2006).

Habitat connectivity - refers to the extent to which a landscape enables or impedes movements of individuals of a given species, either between vital resources (e.g., prey species, browse, water, or shelter) or between populations within a metapopulation. Landscape connectivity, a more general term, connotes the degree to which a landscape facilitates or hinders natural scales of movement for groups of species and, more generally, the spatial continuity of natural cover types across a landscape (Jones 2004).

Indirect effect – the effect of a landscape feature on an organism effectuated over a distance. In this study, these effects are associated with sage-grouse avoidance behavior.

Integer data – data that can be represented as whole numbers. Qualitative and quantitative data can both be expressed as integer data.

Inverse Euclidean Distance – Euclidean distance increases as an object is further away. The inverse Euclidean distance decreases with distance. In the case of sage-grouse behavioral avoidance, for example, the maximum avoidance response of a bird to a resistance feature would occur at distance zero, the location where the bird would encounter the feature. The resistance, therefore, is then calculated as a maximum value at the location of the resistant feature, decreasing in a linear function away from the feature out to the maximum distance where the bird would no longer respond.

Least-cost corridor - the sum of the two CWDs surfaces for a lek kernel pair, where resulting cell values represent the deviation from the associated LCP between the lek kernel pair. Also see normalized least-cost corridor (NLCC).

Least-cost distance (LCD) - The lowest cumulative movement cost between nodes.

Least-cost linkage – Least-cost paths (LCPs) and least-cost corridors.

Least-cost path – the single-cell wide path, from a source node to a destination node, with the least cumulative cost. LCPs were identified and mapped with the Linkage Mapper toolset using the lek kernels data and the CWD surface as inputs.

Lek kernel - localized areas surrounding target leks modeled as being the most accessible to a female sage-grouse moving outward from a given lek in search of a suitable nesting site, identified using the resistant kernel algorithm. These areas serve as both source and destination habitat patches (nodes) between which habitat connectivity for sage-grouse movement was analyzed.

Linkage index – an integrated measure of both linkage quality and average corridor width. See 'Linkage Statistics' for more information.

Linkage quality – This statistic, independent of LCP length, is a measure of the average resistance encountered along an LCP. See 'Linkage Statistics' section for equation.

Linkage robustness - a measure of average corridor width, the availability of multiple, low-resistance routes within a corridor. See 'Linkage Statistics' section for equation.

Linkage zone – broad belts of land with relatively greater habitat continuity. In this study, linkage zones have been delineated by the spatial extent of *normalized least-cost corridors*, or NLCCs.

Mortality risk – the risk of death to a focal organism from landscape or anthropogenic features.

Moving window analysis – see *Focal Operation.*

NLCD – the "National Land Cover Dataset" is a GIS product, produced by the USGS approximately every five years, which classifies each 30m cell to a category of land use (e.g. Developed – High Intensity) or structural vegetation type (e.g. Deciduous Forest). The name of each version of the NLCD includes a year which indicates the date of the imagery that version is based upon. In this case, NLCD 2011 was used as an input to the sage-grouse resistance surface.

Network constellation – a clustered subgroup of nodes (lek kernels) and linkages within a broader network.

Network – see Analysis network.

Node(s) – in connectivity analysis, locations that represent the entities being connected together. In this analysis, these are lek kernels.

Normalized least-cost corridor (NLCC) – A least-cost corridor that is normalized to enable its symbolization with other normalized corridors on a common scale. A least-cost corridor is normalized by subtracting the cost distance of its associated LCP.

Pinch-points – in Circuitscape modeling, pinch-points represent locations of highly constricted (and thus strong) current flow, where connectivity could be severed with the loss of a relatively small amount of dispersal habitat. Pinch-points may therefore represent key places to protect from habitat degradation/alteration.

Polygon – a class of GIS object which represents an area as a series of points (or "vertices") connected by line segments.

Potential functional (habitat) connectivity -- habitat connectivity modeled on landscape structure and limited information on a focal species' dispersal abilities (Fagen and Calabrese 2006). Also see actual functional (habitat) connectivity.

Raster – a GIS data format which consists of a matrix of cells, arranged into rows and columns, where each cell contains a value representing information.

Relative corridor width - a characteristic of NLCCs, reflects the number of alternative routes through similar quality habitat (with wide linkages typically indicative of more potential pathways through higher-quality habitat).

Resistance – an estimate of the cost or impedance to movement of a focal species.

Resistant kernel – A modification of the standard kernel estimator applied to a resistant landscape (Compton et al. 2007).

Sage-grouse - Greater sage-grouse *(Centrocercus urophasianus)*

Search neighborhood – the neighborhood used in a GIS focal function, defined as a maximum search distance and shape of the neighborhood (e.g. square, circle, etc.).

Source – in connectivity analyses, a location that represents a 'from' node to be connected to a 'to' node (or destination).

Structural connectivity (or, continuity) – modeled habitat or landscape connectivity which characterizes the spatial configuration of habitat types across a landscape without attempting to quantify the likelihood of movement by individuals through that landscape. Structural connectivity is traditionally associated with least-cost path analyses and the patch-corridor-matrix model of landscapes, as compared to functional connectivity.

Topology – in a GIS, the rules by which point, line, and polygon features share geometry.

Traversability (metric) – cell metric based on a resistance-weighted spread algorithm (i.e., resistant kernel) to determine the area that can be reached from each cell, expressed as a proportion of the maximum dispersal area under conditions of minimum resistance. [McGarigal et al. 2012).

REFERENCES

Compton, B.W. 2014. CAPS Traversibility metric in R. Version 1.03.

Compton, B.W., K.McGarigal, S.A.Cushman, and L.R.Gamble. 2007. A Resistant –Kernel Model of Connectivity for Amphibians that Breed in Vernal Pools. *Conservation Biology* 21 (3): 788-799.

Crooks, K,R, and M.A. Sanjayan, editors. 2006. Connectivity Conservation. Cambridge University Press, New York.

Doherty K.E., J.D. Tack, J.S. Evans, and D.E. Naugle. 2010. Breeding densities of greater sage-grouse: A tool for range-wide conservation planning. Completion report to the Bureau of Land Management for Interagency Agreement. Issue: L10PG00911.

Donnelly, J.P. et al. 2014. Public lands and private waters: wetland scarcity and land tenure structure sage-grouse distributions. *(In review.)*

Fagan, W.F. and J.M. Calabrese. 2006. Quantifying connectivity: balancing metric performance with data requirements. In: Crooks, K.R. and M.A. Sanjayan (eds.). Connectivity conservation: Maintaining connections for nature. Cambridge University Press. Pgs. 297-317.

Forman, R. T. T. 1995. Land Mosaics. Cambridge, U.K.: Cambridge University Press.

Hagen, C. 2011. Greater Sage-Grouse Conservation Assessment and Strategy for Oregon: A Plan to Maintain and Enhance Populations and Habitat. Oregon Department of Fish and Wildlife, Bend, Oregon. Available at http://www.dfw.state.or.us/wildlife/sagegrouse/docs/20110422_GRSG_April_Final%2052511.pdf Accessed 07/15/2014.

Institute for Natural Resources and The Nature Conservancy, 2014. Oregon Rangeland Decision Support System, V1.0 (In press). Produced for the Sage-Grouse Conservation Partnership (SageCon) - http://oregonexplorer.info/SageCon.

Jones, A. 2004. Graph-theoretic modeling of functional habitat connectivity for lynx on the Okanogan Highlands, northern Washington. Unpublished MS Thesis. Montana State University. Available at: http://scholarworks.montana.edu/xmlui/handle/1/1578

Knick, S.T., S.E Hanser, and K.L.Preston. 2012. Modeling ecological minimum requirements for distribution of greater sage-grouse leks: implicatons for population connectivity across their western range, U.S.A. *Ecology and Evolution* - Open Access, Wiley Online Library.

Manier, D.J., Wood, D.J.A., Bowen, Z.H., Donovan, R.M., Holloran, M.J., Juliusson, L.M., Mayne, K.S., OylerMcCance, S.J., Quamen, F.R., Saher, D.J., and Titolo, A.J., 2013, Summary of science, activities, programs, and policies that influence the rangewide conservation of Greater Sage-Grouse (*Centrocercus urophasianus*): U.S. Geological Survey Open-File Report 2013–1098, 170 p., http://pubs.usgs.gov/of/2013/1098/

McGarigal, K., B.W. Compton, S.D. Jackson, E. Plunkett, and E. Ene. 2012. "Critical Linkages Phase 1: Assessing Connectivity Restoration Potential for Culvert Replacement, Dam Removal and Construction of Wildlife Passage Structures in Massachusetts." Landscape Ecology Program, Department of Environmental Conservation, University of Massachusetts – Amherst. Unpublished report.

McRae, B.H., A.J. Shirk, and J.T. Platt. 2013. Gnarly Landscape Utilities: Resistance and Habitat Calculator User Guide. The Nature Conservancy, Seattle WA. Available at: http://www.circuitscape.org/gnarly-landscape-utilities.

McRae, B.H. 2012a. Barrier Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle WA. Available at: http://www.circuitscape.org/linkagemapper.

McRae, B.H. 2012b. Pinch-point Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle WA. Available at: http://www.circuitscape.org/linkagemapper.

McRae, B.H., S.A. Hall, P. Beier, and D.M. Theobald. 2012. Where to Restore Ecological Connectivity? Detecting Barriers and Quantifying Restoration Benefits. PLoS ONE 7(12): e52604. doi:10.1371/journal.pone.0052604.

McRae, B.H. and D.M. Kavanagh. 2011. Linkage Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle WA. Available at: http://www.circuitscape.org/linkagemapper.

McRae, B.H., and V.B. Shah. 2009. Circuitscape user's guide. The University of California, Santa Barbara. Available at: http://www.circuitscape.org.

McRae, B.H., B.G. Dickson, T.H. Keitt, and V.B. Shah. 2008. Using Circuit Theory to Model Connectivity in Ecology, Evolution, and Conservation. *Ecology* 89(10): 2712-2724.

Schroeder, M.A., and W.M. Vander Haegen. 2003. Migration Patterns of Greater Sage-Grouse in a fragmented landscape. Unpublished Report. Washington Department of Fish and Wildlife, Olympia, Washington.

Smith, Rebecca. 2010. Conserving Montana's Sagebrush Highway: Long-distance Migration in Sage-grouse. Unpublished MS Thesis. University of Montana.

Washington Wildlife Habitat Connectivity Working Group (WHCWG). 2012a. Washington Connected Landscapes Project: Analysis of the Columbia Plateau Ecoregion. Washington's Department of Fish and Wildlife, and Department of Transportation, Olympia, WA.

Washington Wildlife Habitat Connectivity Working Group (WHCWG). 2012b. Chapter 3. Network Centrality, Pinch-Points, and Barriers and Restoration Opportunities for Greater Sage-Grouse (Centrocercus urophasianus) in 'Columbia Plateau Ecoregion Addendum: Habitat Connectivity Centrality, Pinch-Points, and Barriers/Restoration Analyses'.

Washington Wildlife Habitat Connectivity Working Group (WHCWG). 2010. Washington Connected Landscapes Project: Statewide Analysis. Washington Departments of Fish and Wildlife, and Transportation, Olympia, WA.

With, K.A. 1999. Is landscape connectivity necessary and sufficient for wildlife management? In *Forest Fragmentation – Wildlife and Management Implications*, eds. Rochelle, J. A., Lehmann, L.A., and Wisniewski, J., pp. 97-115. Leiden, Boston, Köln, Brill.