Chapter 2. Methods

We took a two-pronged approach to analyzing connectivity across Washington State and portions of adjacent states and British Columbia (Fig. 2.1). First, we developed habitat and connectivity models for 16 focal animal species. We selected these using criteria designed to identify species with geographic ranges, habitat associations, and vulnerabilities to human-created barriers that make them good representatives of the connectivity needs of many species and important ecological processes. We stratified our selection of species to ensure representation of major vegetation types in Washington.

Second, we modeled connectivity between areas of high ***landscape integrity***, i.e., areas that have low levels of human modification and are in relatively natural condition. This approach mirrors that used in the California Essential Habitat Connectivity Project (Spencer et al. 2010) in that it is not tailored to specific species or habitats. It is indifferent to vegetation type—apart from degree of departure from natural conditions—and is intended to provide a coarse filter for species and processes that are sensitive to human disturbance.

Such approaches are not a replacement for species-based analyses but an attempt to cost-effectively identify coarse-filter networks that can then be supplemented by fine-filter planning for species or systems of special concern. They require fewer data and less knowledge about species' habitat associations or behavior (Spencer et al. 2010; Theobald 2010). Still, such approaches are relatively new and their ability to effectively inform conservation planning remains untested. Given the need to understand the relative merits of species- and integrity-based methods for future connectivity analyses within Washington and in other regions, we implemented both in order to provide information needed to evaluate how the methods may be complementary, and to compare their respective strengths and weaknesses.

We used ***cost-weighted distance*** modeling (Singleton et al. 2002; Adriaensen et al. 2003) as the basis for identifying the best linkages connecting habitat blocks (for focal species) and intact natural areas (for landscape integrity). Such analyses produce maps of cumulative movement '***cost***', reflecting barriers or mortality risks encountered, as animals move outward from habitat blocks. They require GIS data layers describing areas to connect and the resistance of the intervening landscape to movement of animals or ecological processes. We developed these for each of our 16 focal species and for four landscape integrity-based models. We then modeled ***least-cost corridors***, which identify continuous swaths of land expected to encompass the best route for a species to travel between habitat blocks. The resulting habitat, integrity, and linkage maps are intended to help identify important areas for connectivity conservation both for the focal species and for more general plant and animal communities.

2.1. Analysis Area

Although our focus is on the connectivity needs of wildlife in Washington State, we expanded our analysis area to incorporate potential linkages to important habitat blocks outside of Washington. We extended the area northward approximately 200 km, eastward 100 km, and southward 130 km to ensure connections with large natural areas in the Coast Range, Cascade

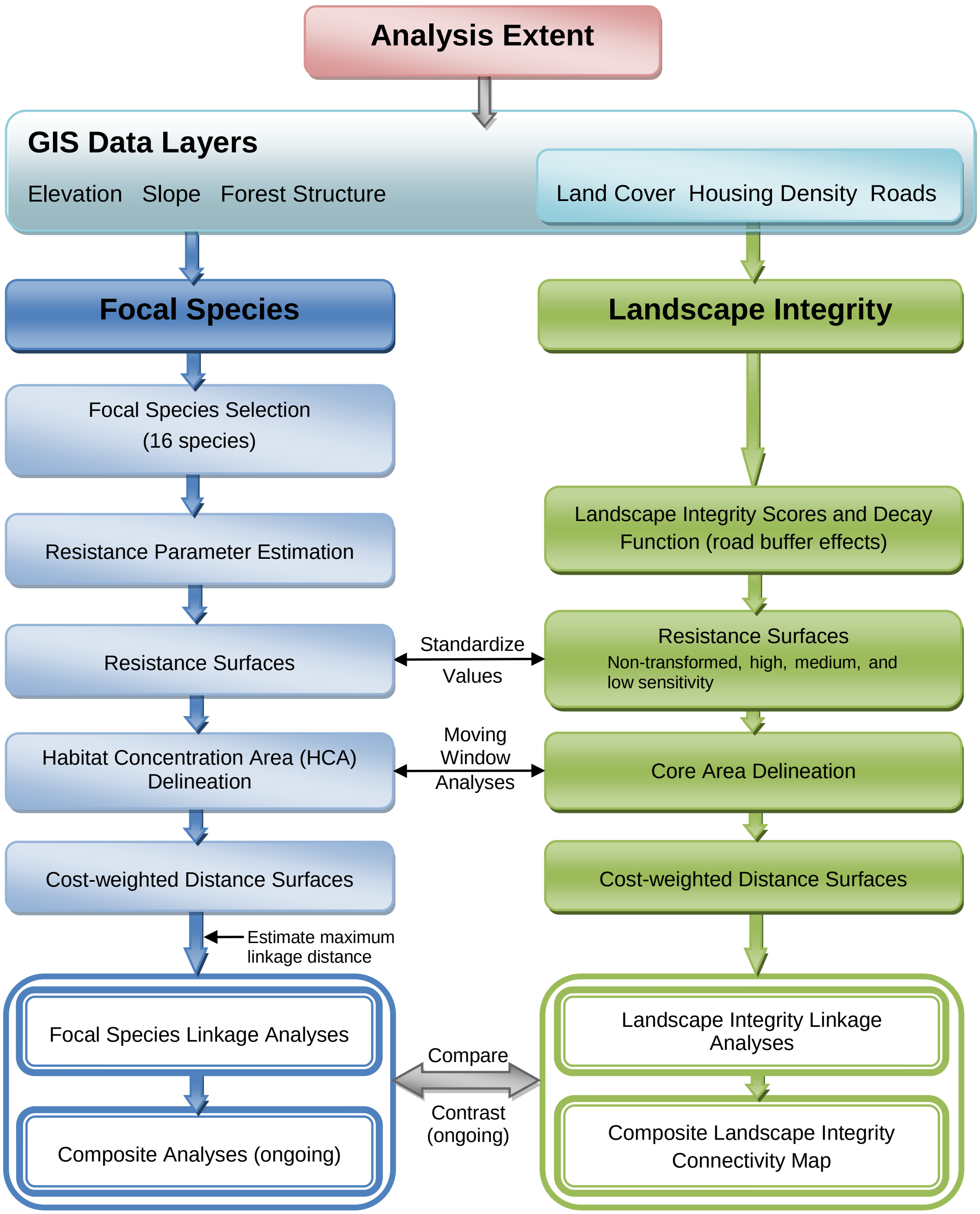

Figure 2.1. Flow of the statewide analysis.

Mountains, and Rocky Mountains in British Columbia, the Rocky Mountains and Columbia Plateau in Idaho, and the Coast Range, Cascade Mountains, Blue Mountains, Wallowa Mountains, and Columbia Plateau in Oregon. The resulting analysis area encompasses 447,000 km^2 of land area, including all of Washington State (except islands in Puget Sound) plus adjacent lands in Oregon, Idaho, British Columbia (excluding islands), and a small portion of Montana (Figs. 2.2 and Fig. 2.3).

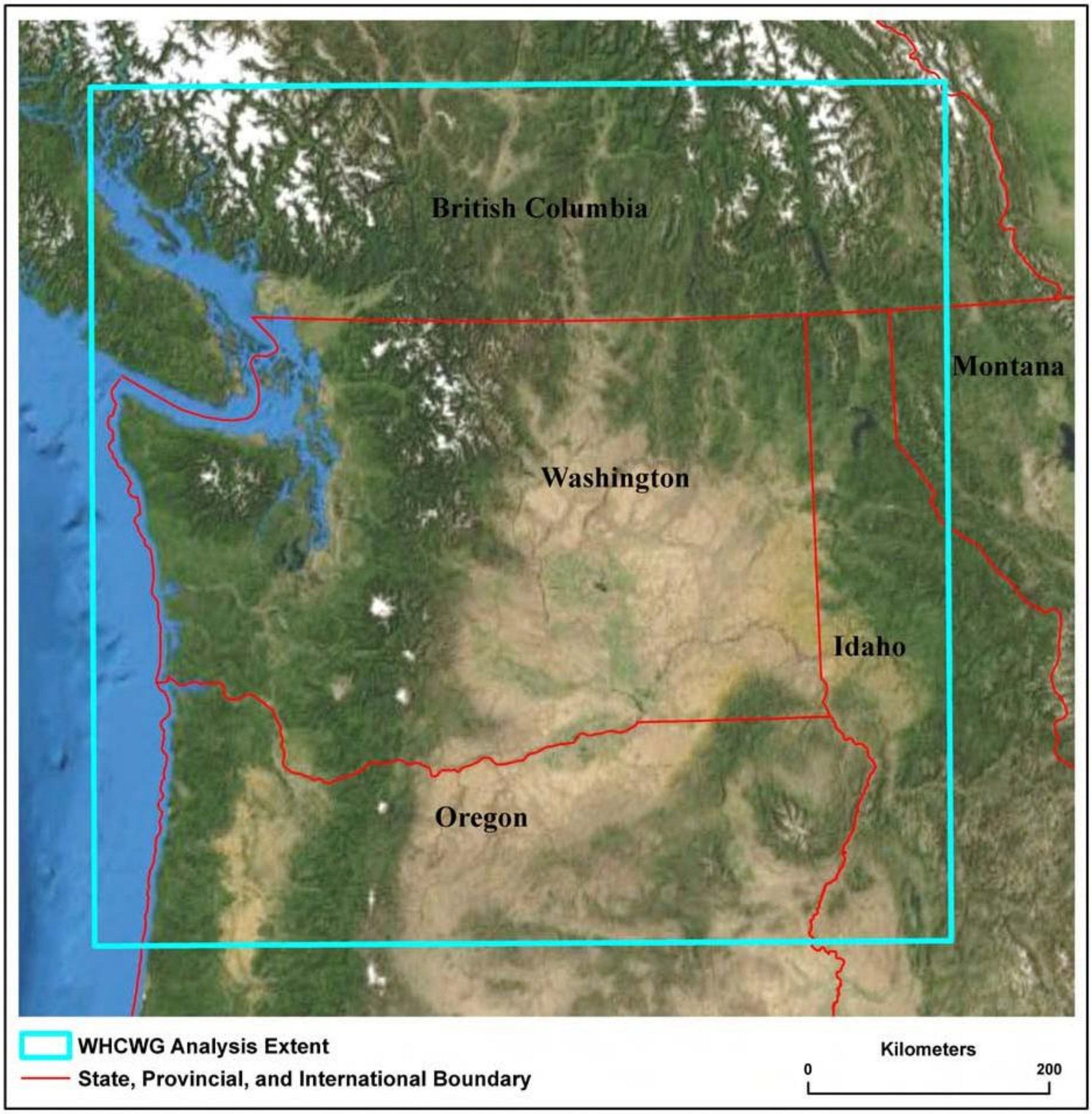

Figure 2.2. Project area map. Analysis extent included all of Washington State (except islands in Puget Sound) plus adjacent lands in Oregon, Idaho, and British Columbia (excluding islands), and a small portion of Montana.

2.2. Data Development

We compiled GIS base data suitable for characterizing wildlife habitat quality and landscape resistance at a broad (statewide plus) scale. These included land cover/land use, elevation, slope, housing density, roads, and forest structural characteristics (Fig. 2.3; Appendix C Figs. C.1–C.5). Ancillary data sets, such as species distribution data, were used as necessary for focal species modeling (See Appendix A for details on species models).

Figure 2.3. Land cover/land-use base layer for project area. See Appendix C (Figs. C.1–C.5) for other base layers.

Development of GIS base layers that were consistent across the entire analysis area often required modification of existing spatial information across jurisdictional boundaries (See Table 2.1 for a summary of our base data sources). All analyses were conducted using an Albers Conical Equal Area map projection with a 100 m square grid cell size. See Appendix C for more detail on data layer development and metadata.

Table 2.1. Summary of GIS spatial data layers used for habitat connectivity modeling.

Spatial Layer	*Summary*
Land Cover/land-use	*USA* – Our primary data source was Northwest Gap Analysis Program (GAP) data. Harvested forest regeneration areas were labeled with an ecosystem type using LANDFIRE Existing Vegetation (EVT) or NW GAP Potential Ecosystem Modifiers. *British Columbia* – Ecosystem boundaries were derived using Biogeoclimatic Subzones/Variant (BGC) data. Forest cover was primarily derived from Vegetation Resource Inventory (VRI) and Baseline Thematic Mapping (BTM).
Forest Structure	*USA* – Forest structure was developed from LANDFIRE Existing Vegetation Cover and LANDFIRE Existing Vegetation Height layers. We filled gaps in a forest cover data near the international border using 2001 National Land Cover Database (NLCD) data. *British Columbia* – VRI was the primary data source for forest cover and height. Data from Earth Observation Sustainable Development (EOSD) and BTM were used in VRI data gaps and in areas where VRI required refinement. In limited areas without any forest information, BGC was used.
Roads	*USA* – We used Washington Department of Natural Resources Transportation data in non-urban areas in Washington, and TIGER/Line Roads Census 2000 data in remaining areas. *British Columbia* – We used Digital Road Atlas (DRA) data for all road classes.
Housing Density	*USA* – We obtained housing density data from a raster layer based on US Census 2000 data. The data were compiled using methods described by the U.S. Environmental Protection Agency (2009). *British Columbia* – Dwelling counts were derived from 2001 Statistics Canada total private dwellings census subdivision-level summaries. Census subdivision polygons were partitioned with polygons primarily from Singleton et al. (2002) and BTM to isolate areas of human development. Housing counts were linked to the partitioned polygons.
Elevation	*USA* – Elevation data were assembled from the USGS 1 arc second, 30-meter National Elevation Dataset (NED). *British Columbia* – Elevation data were derived from the 25-meter Terrain Resource Information Management (TRIM) elevation layer.
Slope	We derived slope data using a mosaic of the USA and British Columbia elevation data described above.

2.3. Focal Species Selection

A carefully chosen set of focal species can serve an “umbrella” function by encompassing the diverse habitat needs of a broader array species of conservation concern (Roberge & Angelstam 2004; Beier et al. 2008). We chose focal species that we believed would efficiently represent the connectivity needs of wildlife species for which coarse-scale (statewide-level) planning is relevant. We also chose species that were sensitive to landscape features of interest to planners, such as transportation infrastructure and urban development.

Focal species selection followed a series of carefully reviewed steps (Fig. 2.4). To begin constructing a list of candidates for selection, we identified sources of population status ranking information that would give us a list of species with demonstrated declines or known vulnerabilities—potential indications of the effects of human-induced habitat change. Our list was initially composed of Washington's native vertebrate species with NatureServe Global or State Ranks of G1, G2, or G3 or S1, S2, or S3.

We then reviewed Washington's list of Species of Greatest Conservation Need (WDFW 2005), adding those that weren't already included by virtue of their state or global rank. Finally, we reviewed the list of species identified by the WDFW Landscape Priority Habitats and Species (PHS) project (WDFW 2009) as having High Sensitivity or Very High Sensitivity to development. Specifically, we added those that were members of a response group indicating movement over broad spatial scales and/or those that were indicated as having sensitivity to loss of connectivity or a negative response to the presence of roads or traffic.

To ensure that focal species represented a range of ecoregions and ecological systems in the state, we used the National Vegetation Classification Standard (NVCS) to divide the state into five dominant vegetation classes. These included: (1) Semi-desert, (2) Northern Rocky Mountain Forests, (3) Vancouverian Forests, (4) Subalpine Forests, and (5) Alpine Rock, Grassland and Shrubland (Fig. 2.5). All of the candidate focal species were assigned to one or more habitat associations (Cassidy et al. 1997; Johnson & O'Neil 2001).

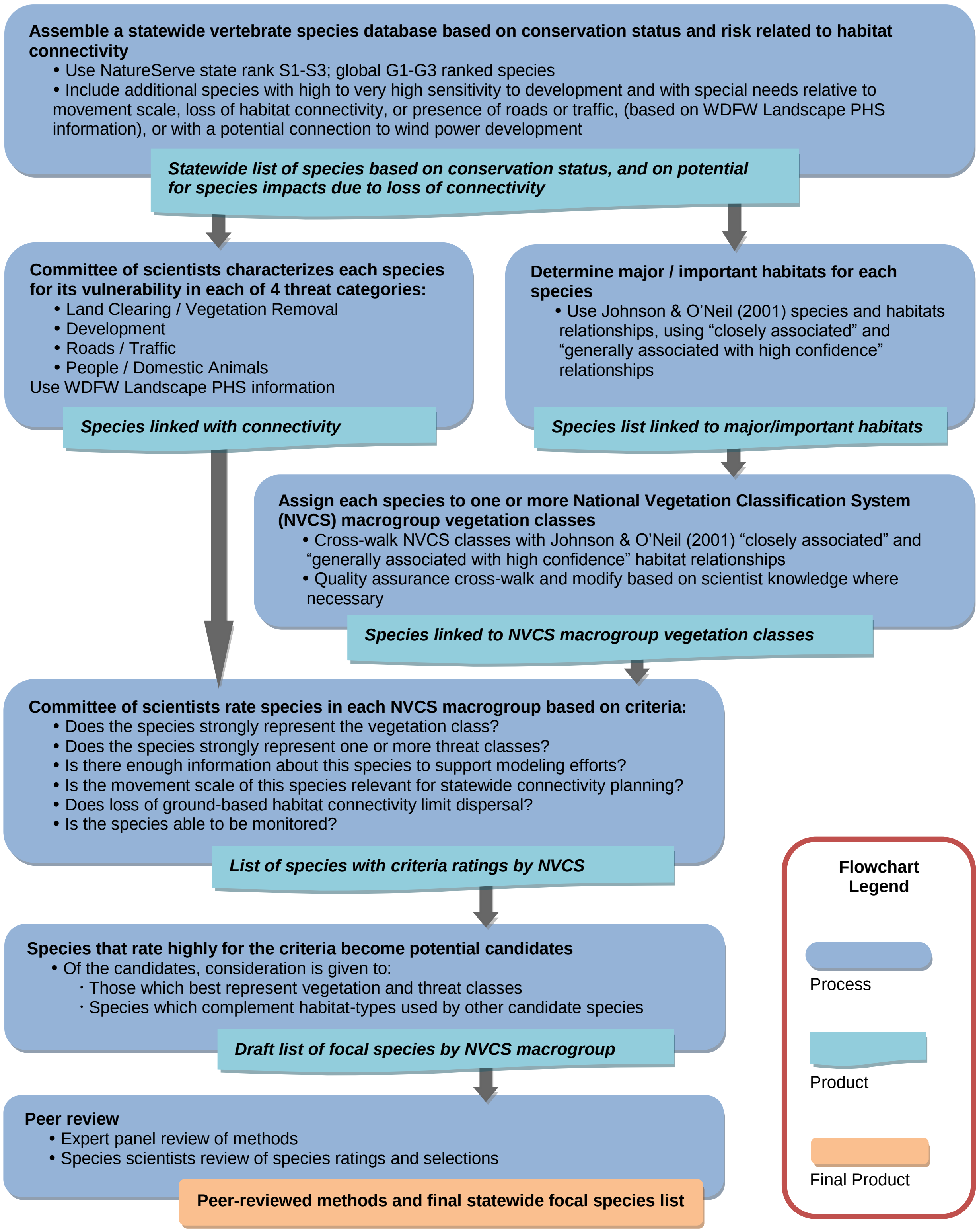

Figure 2.4. Schematic of focal species selection methods.

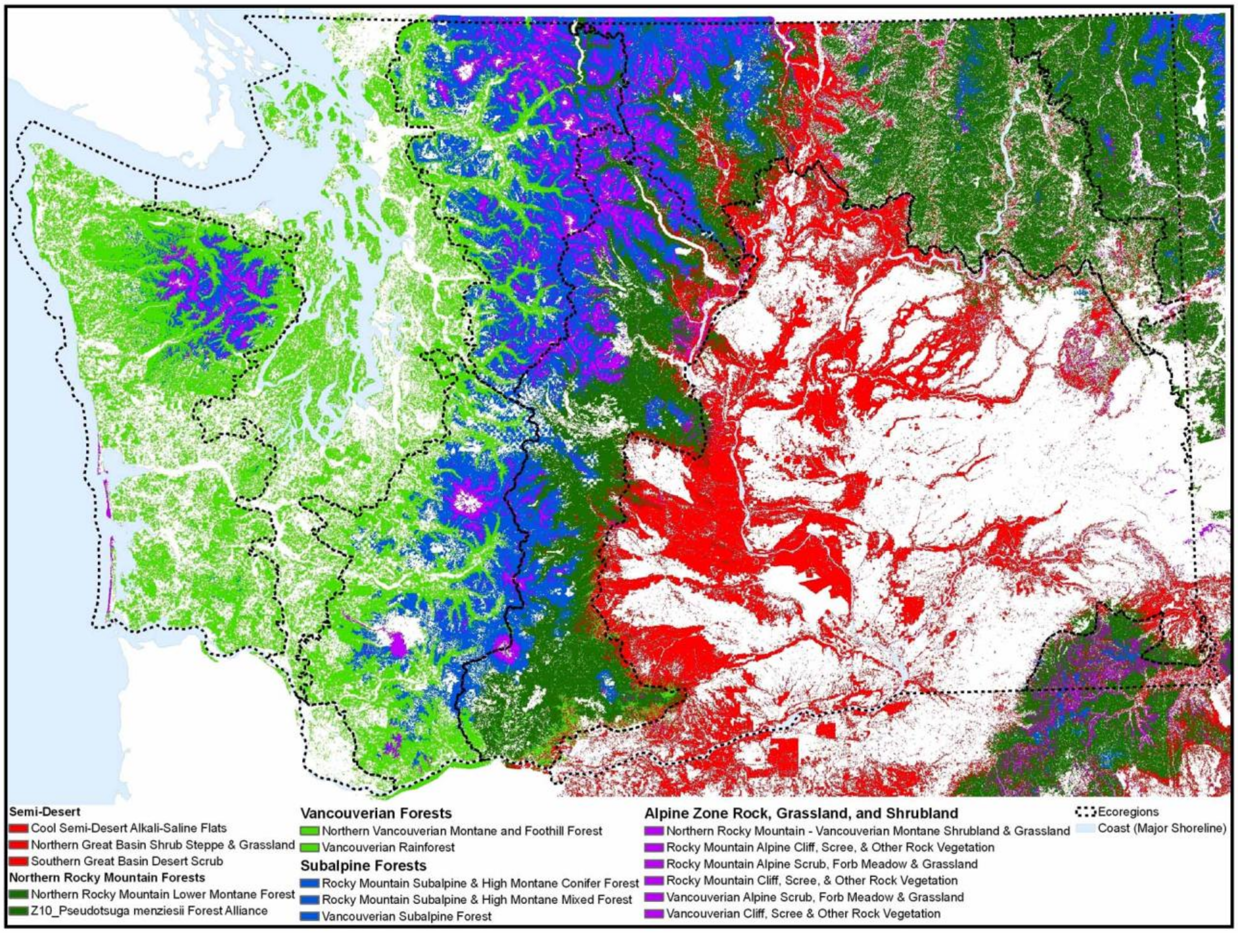

Figure 2.5. Major vegetation classes in Washington used to stratify focal species selection. Note: lands that do not contain one of the five major vegetation classes (including those converted to human uses and all lakes) are shown in white.

Each species was evaluated for its vulnerability to threats and barriers to movement caused by human-created landscape changes. We identified four overarching types of threats/barriers and their potential effects on focal species' movements:

1) *Land clearing/vegetation removal*, which limits connectivity through
   - ***Alienation*** due to lack of security cover
   - Change to inhospitable environment (e.g., desiccating conditions for amphibians)
   - Alienation due to lack of forage or prey
   - Increases in competing species, predators, invasive exotics

2) *Buildings and Infrastructure*, which limit connectivity through
   - Barriers to movement created by fences, walls, buildings, asphalt, canals, etc.
   - Alienation due to noise, lighting, lack of forage or prey
   - Increases in competing species, predators, invasive exotics
   - Making important habitat areas inaccessible (e.g., streams diverted into culverts)

3) *Roads and Traffic*, which limit connectivity through
    - Creation of inhospitable conditions (e.g., desiccating conditions for amphibians)
    - Creation of physical barriers (e.g., Jersey or Texas barriers, right-of-way fences)
    - "Fatal attraction" (e.g., attraction of snakes to warm road surface)
    - Increased mortalities due to collisions
    - Behavioral alienation (i.e., avoidance of roads or high traffic volumes)

4) *Presence of people or domestic animals*, which limit connectivity through
    - Legal harvest and poaching
    - Harassment and disturbance
    - Disease transmission (e.g., domestic sheep to bighorn sheep [*Ovis canadensis*])
    - Intolerance (e.g., conflict resolution removals)

Species identified as vulnerable to one or more of the overarching threats to habitat connectivity (See Table 2.2) were further evaluated against six criteria to determine whether each would make a good focal species choice. The criteria were:

1) *Is the species a good representative of the vegetation class?* We sought to identify species that were broadly distributed within a vegetation class and associated habitat conditions typically found there. Species with a very limited range within the class were considered to be poor choices compared to species that were more broadly distributed in the vegetation class.

2) *Is the species representative of most or all of the threat classes?* The intent of this criterion was to assure that the species chosen were, as intended, vulnerable to movement impairments caused by human-created landscape changes. Priority was given to those species considered vulnerable to multiple threats.

3) *Is there enough information on the species to support modeling efforts?* Suitable focal species are those for which there is available information on conditions that promote or deter movements; species we know more about are better candidates for modeling than those with less information.

4) *Are the species' movement choices based on features that are coarse enough for modeling?* A suitable focal species must make habitat selection choices at scales that are reasonably matched to the scale of the GIS data used for modeling. For statewide modeling, documented home range sizes and ***dispersal*** distances were used as a surrogate for the animal's scale of habitat selection. If either suggested short-term movement capabilities of at least 10 km, the species was considered compatible with the statewide modeling scale. Species with more restricted movement capabilities require analyses at finer (ecoregional, local) scales.

5) *Is the species sensitive to habitat barriers?* We focused on identifying species whose movements can be limited by human-created landscape alterations. Most of the identified species move on the ground and would be sensitive to barriers. Highly mobile species that easily move through human-altered landscapes were discarded.

6) *Can the species be monitored?* The best focal species are those that can be monitored to understand the effects of human-created barriers to movements, validate model results, and evaluate effectiveness of efforts to conserve and restore habitat connectivity. This criterion was used as a "tie breaker" when multiple species were equally ranked based on other criteria.

For each of the above-listed criteria, we rated candidate species as *excellent*, *acceptable*, *marginal*, or *poor*. In cases where multiple species scored similarly, we chose the best representative and excluded the others from further consideration. We stress that because we limited our focal species to those appropriate for modeling at the statewide scale (See item 4 above), our focal species may not represent the needs of species with more limited movement capabilities. Such species will be better addressed by future analyses at ecoregional and local scales.

Table 2.2. Vertebrates identified as highly vulnerable to loss of terrestrial habitat connectivity.

Birds	*Mammals*	*Amphibians*	*Reptiles*
Bald Eagle	American badger*	Cascade torrent salamander	California mountain kingsnake*
Common Poorwill	American marten*	Cascades frog	night snake
Ferruginous Hawk	bighorn sheep	Columbia spotted frog*	Pacific gopher snake*
Flammulated Owl	American black bear	Columbia torrent salamander	Pacific pond turtle*
Golden Eagle	black-tailed jackrabbit*	Cope's giant salamander	painted turtle
Gray Flycatcher	California myotis	Dunn's salamander	pygmy horned lizard
Great Blue Heron	Columbian white-tailed deer*	Larch Mountain salamander	ring-necked snake
Great Gray Owl*	cougar	northern leopard frog*	rubber boa
Greater Sage-Grouse*	elk*	northern red-legged frog	sagebrush lizard
Gyrfalcon	fisher*	Olympic torrent salamander	sharp-tailed snake
Lapland Longspur	fringed myotis	Oregon spotted frog	side-blotched lizard
Lewis' Woodpecker	gray wolf*	Rocky Mountain tailed frog	striped whipsnake*
Long-eared Owl	gray-tailed vole	tiger salamander*	western rattlesnake
Merlin	grizzly bear*	Van Dyke's salamander	western yellow-bellied racer*
Mountain Quail	hoary marmot	western toad*	
Northern Goshawk	least chipmunk	Woodhouse's toad	
Northern Spotted Owl*	long-legged myotis		
Pileated Woodpecker*	Canada lynx*		
Prairie Falcon	Merriam's shrew		
Pygmy Nuthatch*	moose		
Sharp-tailed Grouse*	mountain caribou*		
Short-eared Owl	mountain goat		
Snow Bunting	mule deer		
Spruce Grouse	northern flying squirrel		
White-breasted Nuthatch	Olympic marmot*		
White-headed Woodpecker	pygmy rabbit*		
White-tailed Kite	pygmy shrew		
White-tailed Ptarmigan	red-tailed chipmunk		
Williamson's Sapsucker	sagebrush vole		
	silver-haired bat		
	Townsend's big-eared bat*		
	Townsend's ground squirrel*		
	Washington ground squirrel*		
	western gray squirrel*		
	western pocket gopher*		
	white-tailed jackrabbit*		
	wolverine*		
	yellow-bellied marmot		

*Species of Greatest Conservation Need (SGCN; WDFW 2005). For elk, western yellow-bellied racer, and gopher snake, only the Nooksack elk herd and the extirpated western Washington populations of gopher snake and yellow-bellied racer are SGCN.

2.4. Resistance Models

Cost-weighted distance models require GIS data layers that quantify estimates of the resistance presented by different landscape features to movement of animals or ecological processes (Singleton et al. 2002; Adriaensen et al. 2003; Beier et al. 2008). For focal species-based analyses, we developed resistance layers for each of the 16 species using species-specific ***dispersal habitat*** suitability models. For landscape integrity-based analyses, we developed resistance layers by reviewing and adapting published models with similar aims.

2.4.1. Focal Species Resistance Parameters

For each of the 16 focal species, we assigned relative resistance values to different landscape features, such as different classes of roads or various land cover/land-use types (See Appendix C for GIS base layers). Conceptually, we defined the resistance contributed by each landscape feature as the number of additional grid cells of ideal habitat a given species would move through to avoid one grid cell of the feature being considered. For each landscape feature, we estimated the additional resistance to movement imposed by the feature relative to "ideal" habitat, ranging from zero for ideal habitat to infinity for complete barriers. The final resistance layer for each species was then derived by summing the resistances from each input layer and adding one (to account for ***Euclidean distance***). Each cell in the resulting resistance layer for each species had a resistance value summing the individual resistances from up to six GIS base layers, including land cover/land-use, elevation, slope, housing density, roads, and forest structure.

In practice, scoring features required using professional judgment to synthesize how factors would limit movement through behavioral responses (e.g., avoidance of roads) and through mortality (e.g., vehicle collisions). In most cases, the parameters used to build each resistance model were developed based on literature review and expert judgment. In one case, mountain goats (*Oreamnos americanus*), we used an analysis of genetic data from our study area (Shirk et al. 2010) to assist in parameterization (See Appendix A for details of species models).

Species experts external to our project reviewed and critiqued draft resistance models. A master list of resistance parameters is provided in Appendix B.

2.4.2. Landscape Integrity Resistance Parameters

For our landscape integrity-based analyses, we adapted methods developed elsewhere to create an index of human impacts to lands across our study area, which we refer to as ***landscape integrity***. We then used this index to develop a set of resistance layers reflecting a range of hypotheses as to how human alterations affect connectivity for species and for ecological processes.

LANDSCAPE INTEGRITY MAP

We developed a map of landscape integrity by adapting the methodology used by NatureServe in developing a similar map of national landscape condition (Comer & Hak, unpublished). Comer and Hak's approach is similar in intent to a series of spatially explicit indices of human ecological impact, including Sanderson et al. (2002), Leu et al. (2008), and Theobald (2010). These indices all provide a spatially explicit ranking of the degree of human impact on the integrity of ecosystems, their component organisms, and processes. While we use the term *landscape integrity*, it is analogous to *landscape condition* (Comer & Hak, unpublished), *human footprint* (Sanderson et al. 2002; Leu et al. 2008), and *landscape naturalness* (Theobald 2010). We decided not to use existing human footprint maps for two main reasons: (1) we wanted landscape integrity and focal species analyses to be as consistent as possible, including using the same base data, in order to compare results between the two approaches, and (2) we wanted a human footprint map that was consistent across jurisdictional boundaries (i.e., the U.S. and Canada).

To assure comparability with the focal species connectivity maps and to provide coverage into British Columbia, we applied Comer and Hak's parameter values (multiplied by 10, to convert to a range of 1–10) to the same GIS base layers used in our focal species analyses for land cover/land-use, housing density, and roads. All grid cells in the study area were assigned a landscape integrity score based on the minimum score for all data layers used in the model (Table 2.3). We also used the distance from road categories defined by focal species models. Although Comer and Hak's methods used a decay function to model effects of roads on integrity of adjacent areas, we used the focal species buffer distances and interpolated buffer landscape integrity scores assuming a linear relationship from the road feature to the outer buffer distance.

Table 2.3. Landscape condition factors and associated values used to describe landscape integrity on the study area, modified from Comer and Hak (unpublished) as described above.

Data Source	*Condition*	*Landscape Integrity Value*
Land cover/land-use	urban/developed	0.5
	agricultural lands	3.0
	water	5.0
	all other land cover	9.0
Housing density	≤10 acres per dwelling unit	0.5
	>10 to ≤40 acres per dwelling unit	5.0
	>40 to ≤80 acres per dwelling unit	6.0
	> 80 acres per dwelling unit	9.0
Freeways and major highways	centerline	0.5
	>0–500 meter buffer	3.0
	>500–1000 meter buffer	7.0
Secondary highways	centerline	2.0
	>0–500 meter buffer	3.0
	>500–1000 meter buffer	7.0
Local roads	centerline	5.0
	>0–500 meter buffer	8.0
No roads		9.0

LANDSCAPE INTEGRITY RESISTANCE MODEL

Landscape integrity values (Table 2.3) reflect generic ecological conditions, and were not developed with the movement behavior of specific classes of animals in mind. Because there is no clear way to translate integrity into resistance, we developed four resistance models based on differing hypotheses about the relationship between landscape integrity and resistance. The first used a simple linear transformation of the landscape integrity scores assigned to all grid cells (Table 2.3) for all *LI* values <9.0:

$$R_{LI} = 10 * (10 - LI) - 9$$

Where R_{LI} is the resistance used in the linear resistance model, and *LI* is the minimum landscape integrity value (Table 2.3) at each grid cell, taken across all input layers. The value of 9 was subtracted from the transformed value to set the lowest resistance value to 1.0, following the convention used in focal species models.

In addition to the resistance model based on the simple linear transformation above, we created three resistance models reflecting different levels of sensitivity to human modification. These were designed to more closely correspond to ranges of resistances assigned to human-modified landscapes in the focal species models (which had maximum resistances ranging from 100 to 10,000). To create resistance models reflecting low, medium, and high sensitivities to human modification, we transformed the landscape integrity values so that areas with greatest human alteration were 100, 1000, and 10,000 times more resistant to movement than the least altered areas (representing the smallest, median, and largest maximum resistance values used in the suite of 16 focal species models, respectively);

$$R_{sens} = (10 - LI)^{P_{sens}}$$

Where R_{sens} is the resistance derived for each sensitivity model, and *LI* is the minimum landscape integrity value (Table 2.3) at each grid cell, taken across all input layers. P_{sens} is a constant chosen for each sensitivity model such that the maximum value of R_{sens} is 100, 1000, or 10,000 for the low, medium, and high sensitivity models respectively.

The transformed resistance values used to create the different resistance layers for landscape integrity modeling are provided in Appendix B; example values for different features are shown in Fig. 2.6.

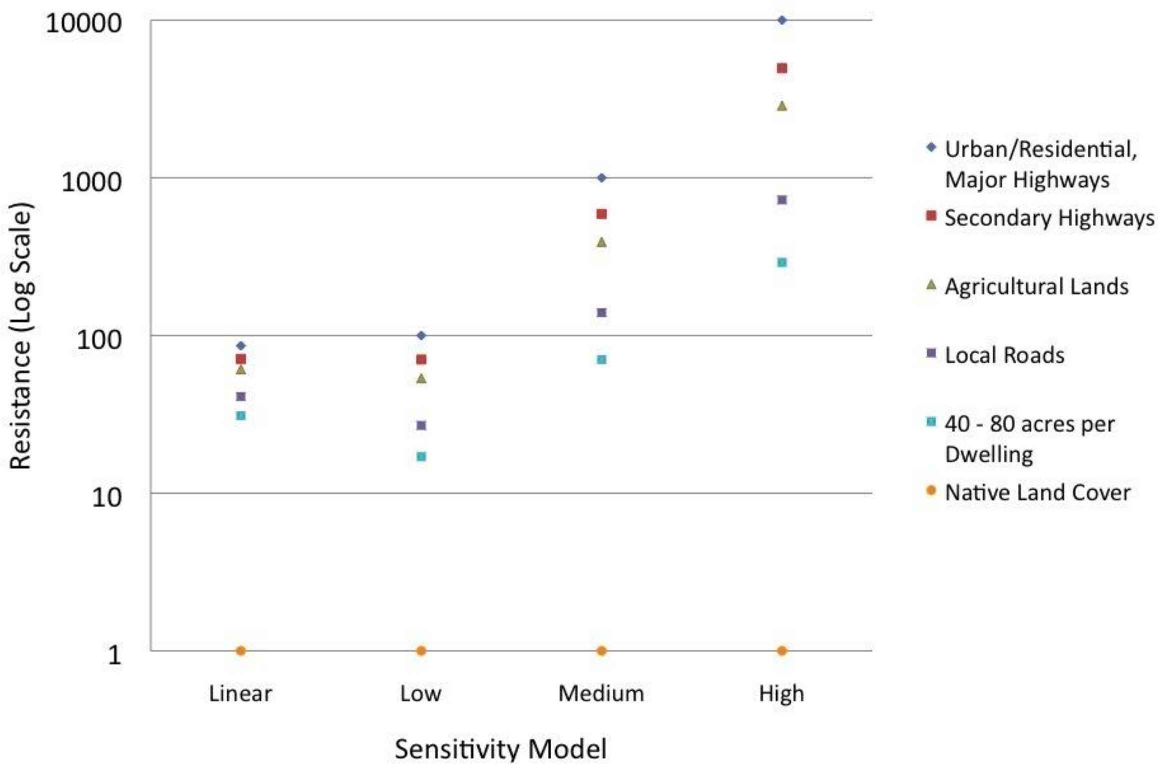

Figure 2.6. Resistance values (R_{sens}) for selected model parameter conditions for each of the four sensitivity models used in the landscape integrity connectivity analysis.

2.5. Delineating Areas Important to Connect

2.5.1. Focal Species Habitat Concentration Areas

We use the term ***habitat concentration area*** (HCA) to refer to areas between which we evaluated patterns of habitat connectivity for focal species. Habitat concentration areas are defined as significant habitat areas that are expected or known to be important for focal species based on actual survey information or habitat association modeling. We used known centers of distribution for species whose populations and habitats have been documented through extensive surveys, including bighorn sheep, mountain goat, Greater Sage-Grouse, and Sharp-tailed Grouse (*Tympanuchus phasianellus*, Appendix A).

For species with extremely broad or poorly defined populations, we defined HCAs using habitat models following these steps:

1) Develop a binary habitat surface where each grid cell in a ***raster*** is designated as either habitat or non-habitat based on habitat suitability models using the GIS base layers compiled for this project. Habitat suitability models were identical to resistance models for black-tailed jackrabbit (*Lepus californicus*), white-tailed jackrabbit, American badger, American black bear, Canada lynx (*Lynx canadensis*), mule deer, and northern flying squirrel. Habitat suitability differed from resistance for elk, wolverine, western gray squirrel (*Sciurus griseus*), and western toad. Habitat suitability and resistance models are described in Appendix A.

2) Calculate the proportion of habitat within a circular ***moving window*** with an area equal to the species' home range size. This step generated a surface representing where the largest concentrations of habitat exist.

3) Delete habitat cells in areas where habitat is sparse. We removed habitat cells from the binary habitat raster if the proportion of habitat within a home range radius was <0.5. This prevented habitat concentrations from forming in areas where habitat is not sufficiently concentrated.

4) Join remaining habitat cells together if they are within a home range movement distance. We expanded the designated habitat area outwards (from the remaining habitat cells after step 3) up to a total cost-weighted distance equal to the species home range movement radius. This has the effect of joining nearby habitat cells together if the intervening landscape supports within-home range connectivity.

5) Eliminate small patches unlikely to contribute significantly to a species' habitat. We calculated the area of each habitat patch and removed those patches where the area was less than a species-specific threshold.

2.5.2. Landscape Integrity Core Areas

The landscape integrity approach links together large, contiguous patches, or core areas, of high landscape integrity. To identify core areas, we used the same computational methods used to identify focal species HCAs described above and following these rules:

1) Core area minimum size = 10,000 acres (4047 ha) for all ecoregions.

2) Core areas only include native land-cover types.

3) Core areas do not include freeways, major highways, or secondary highways.

4) Core areas can include local roads, but local road density must be ≤10%, except:

    a. West Coast Ecoregion, where road density must be ≤20%.
    b. Willamette Valley-Puget Trough-Georgia Basin Ecoregion, where road density must be ≤30%.

We selected a 10,000 acre (4047 ha) minimum to represent areas large enough to allow for natural disturbance processes (R. Crawford, personal communication; Spencer et al. 2010). The local road density layer was created using a 20 x 20 grid cell moving window on the Local Roads raster layer. Density values were calculated by the number of grid cells containing local roads divided by the total number of cells in the window (i.e., 400).

2.6. Linkage Modeling

In this section we describe methods for mapping linkages using the resistance and HCA/core area layers described above. Although we refer to *HCAs* and *species* throughout for simplicity, these methods also apply to linkages connecting landscape integrity core areas.

Cost-weighted distance maps represent the least accumulative cost required to move between a cell and a specified source. The cost accumulated by moving through each intermediate cell is equal to the cell's resistance value multiplied by the cell size (100 m in the case of this study). For example, if a given target cell is two cells away from a specified source, and both of the intervening cells have a resistance value of 5, the cost accumulated moving from the source through the two cells is 1000 m. However, if there is an alternate route that passes through four cells, each with a resistance of 1, the cost distance at the given cell would be 400 m. The central concept in these analyses is that the cost distance from a source to a cell increases as the resistance of the intervening landscape (measured along the most efficient path from the source to the target cell) increases.

We used the ArcGIS Cost Distance function to create cost-weighted distance maps representing, for each target cell, the minimum sum of cell costs accumulated as an animal moves from the nearest HCA to the target cell. The resulting map provides an estimate of the relative "accessibility" of each cell to the nearest HCA, considering the cumulative effect of features that facilitate or impede movement (Singleton et al. 2002). This map is particularly useful for identifying barrier effects and broad areas that contribute to connectivity.

Least-cost corridor maps represent the cost of moving between a *specific pair* of HCAs through any given cell on the landscape by calculating, for that cell, the sum of cost-weighted distances from the cell to each of the HCAs. The result is a map that shows the relative value of each grid cell in providing connectivity between the HCA pair, allowing users to identify which routes encounter more or fewer features that facilitate or impede movement while moving between the two HCAs.

2.6.1. Linkage Modeling Algorithms

We automated our linkage modeling by developing a set of Python scripts bundled as an ArcGIS toolbox. The scripts took the HCA and resistance layers described above as input, and automatically mapped least-cost corridors between adjacent HCA pairs. To display multiple least-cost corridors on a single map, we normalized each corridor by subtracting its minimum cost-weighted distance. Thus, the ***normalized least-cost corridor*** between HCA *A* and *B* was calculated by the following formula:

$$CWD_A + CWD_B - LCD_{AB}$$

Where CWD_A is the cost-weighted distance from HCA *A*, CWD_B is the cost-weighted distance from HCA_B, and LCD_{AB} is the cost-weighted distance accumulated moving along the ideal (least-cost) path connecting the HCA pair. This step mapped all corridors in the same "currency;" grid cells in each normalized corridor raster range in value from 0 (the best or least-cost path) on up. Cell values were still in cost distance units, and reflected how much more costly the (locally optimal) path between the HCAs passing through each cell was relative to the (globally optimal) least-cost path connecting the HCA pair. The normalized corridor maps were then combined using the ArcGIS Mosaic function to create a composite linkage map in which each cell represented the minimum value of all individual normalized corridor layers. The scripts also generated linkage statistics (e.g., ratio of cost-weighted distance to Euclidean map distance) that are informative for comparing and ranking linkage quality and degree of connectivity between HCA pairs.

Taken together, the linkage maps and linkage statistics are useful for comparing the contribution to functional habitat connectivity of different portions of the landscape. Additional documentation of these scripts is provided in Appendix D and linkage statistics are provided in Appendix E.

2.6.2. Focal Species Linkage Modeling

For most focal species, we limited the length the least-cost path of each mapped linkage between a pair of HCAs to a maximum cost-weighted distance value, discarding linkages with ***least-cost distances*** that exceeded this value (Table 2.4). Values were chosen based on documented movement events from the literature and expert judgment. Table 2.5 illustrates how maximum cost-weighted distance values and per-cell resistance values combine to affect modeled movement potential for a hypothetical species. The underlying concept is fairly simple: an animal cannot successfully move as far through land cover types that are difficult or hostile as it can through other types.

Table 2.4. Maximum cost-weighted distances specified for focal species linkage modeling. See Appendix A for details regarding individual species.

Focal Species	*Maximum corridor length, in cost-weighted distance units*
Sharp-tailed Grouse	80 km
Greater Sage-Grouse	200 km
American badger	301 km
Black-tailed jackrabbit	no limit
White-tailed jackrabbit	no limit
Mule deer	250 km
Bighorn sheep	1000 km
Western gray squirrel	200 km
American black bear	400 km
Elk	250 km
Northern flying squirrel	126 km
Western toad	51 km
American marten	300 km
Canada lynx	1350 km
Mountain goat	200 km
Wolverine	1500 km

The normalized least-cost corridor algorithms produced “wall-to-wall” linkage maps, with every grid cell in the study area having a value that represented its deviation from the least-cost movement route. To create linkage maps focusing on portions of ***linkage zones*** relevant for planning, we truncated normalized corridors by displaying only values from zero to a species-specific ***linkage mapping cutoff***. Doing so required making decisions about cutoff values, with higher values resulting in mapped linkage zones that were wider, on average (normalized corridors will narrow when passing through high-resistance habitat because cost-weighted distance accumulates more quickly there). We chose cutoff values that would represent linkage zones of relatively uniform width across species despite significant differences between species in landscape resistance values. We chose values that produced generous linkage zone widths due to the coarse scale of the analysis and the intent that linkage zones serve not only focal species, but other species and processes as well. Wider linkage zones also reflect the uncertainty in GIS base data, resistance models, and other parameters used in our modeling process; in other words, the precision implied by mapping narrower linkages would have suggested a greater ability to identify exact locations on the landscape that are important for movement than is warranted (See Chapter 4).

Table 2.5. Example effects of per-cell resistance values on movement ability under different maximum cost-weighted distance values.

Per-cell resistance value of landscape feature (ideal conditions assigned a value of 1)	*Cost-weighted distance, in meters, accumulated by moving through one cell (resistance value x 100 m per cell)*	*Maximum Euclidean distance species can travel through each landscape feature when limited to a max cost-weighted distance of:*	
		10 km	*200 km*
1	100	10 km	200 km
2	200	5 km	100 km
5	500	2 km	40 km
10	1000	1 km	20 km
20	2000	500 m	10 km
50	5000	200 m	4 km
100	10,000	100 m	2 km
1000	50,000	20 m	400 m

To meet the above criteria, we chose linkage mapping cutoffs of 10, 25, and 75 km in cost-weighted distance. Species characterized as rapidly accumulating cost when moving through suboptimal habitat (American marten [*Martes americana*], bighorn sheep, American black bear, Canada lynx, and western gray squirrel) were assigned cutoffs of 75 km. Species characterized as capable of moving easily through suboptimal habitat (western toad and mountain goat) were assigned cutoffs of 10 km. All other focal species were assigned cutoffs of 25 km.

2.6.3. Landscape Integrity Linkage Modeling

We created four landscape integrity-based linkage maps using, respectively, the four resistance layers described in section 2.4.2. We allowed adjacent core areas within 160 km (100 mi) Euclidean distance of each other to be connected, with no maximum cost-weighted distance. We chose this conservative threshold to make as few restrictive assumptions as possible about maximum movement distances for ecological elements.

Because an identical set of core areas was used in each of the four linkage models, it was possible to additively combine them in a single composite map to identify lands that were most robust to sensitivity assumptions. To do this, we normalized each of the combined least-cost corridor rasters into 100,000 equal-area bins, then summed raster values across all connectivity models to create one composite map. To examine differences in connectivity areas identified among resistance models, we extracted each connectivity raster to include only the top 30% area (raster values <30,000) of the landscape, ranked in order of normalized least-cost distances. These four 30% connectivity zone rasters were then overlaid to show areas identified by one, two, three, or all four resistance models. Those connectivity areas associated with the greatest number of models were considered most robust to assumptions of sensitivity to human influence.

2.6.4. Network Correspondence Analysis

To identify common patterns across focal species and landscape integrity analyses, we first defined binary ***linkage networks*** based on modeling results for all 16 focal species and the medium sensitivity landscape integrity model. We defined the linkage network for each focal species (or landscape integrity) to include: (1) the HCAs (or integrity core areas), (2) the normalized least-cost corridors up to a species- or integrity-specific network cutoff, and (3) a cost-weighted distance buffer surrounding the HCAs or integrity core areas using the same cutoff value.

We then overlaid the networks and quantified the degree of overlap across them. To do this, we generated a systematic grid of points at a 2.5 km square interval across the state of Washington (*n* = 27,695). Each point in this grid was categorized as being in or out of each focal species or landscape integrity network. We assessed 3 different network cutoff values to determine whether overlap patterns were sensitive to the area that was included in the network. The network cutoff definitions for the focal species were based on the linkage mapping cutoff values (listed above in section 2.6.2), and included wide (100, 50, or 20 km), moderate (50, 25, or 10 km), and narrow (25, 13, or 5 km) cutoff ranges (Table 2.6). Network cutoffs for the landscape integrity network were based on a qualitative comparison with the focal species networks (Table 2.6).

Table 2.6. Network cutoff values (km cost-weighted distance) used to define the focal species and landscape integrity networks for this analysis.

Network	*Wide*	*Moderate*	*Narrow*
Sharp-tailed Grouse	50	25	13
Greater Sage-Grouse	50	25	13
American badger	50	25	13
Black-tailed jackrabbit	50	25	13
White-tailed jackrabbit	50	25	13
Mule deer	50	25	13
Bighorn sheep	100	50	25
Western gray squirrel	100	50	25
American black bear	100	50	25
Elk	50	25	13
Northern flying squirrel	50	25	13
Western toad	20	10	5
American marten	100	50	25
Canada lynx	100	50	25
Mountain goat	20	10	5
Wolverine	50	25	13
Landscape integrity	400	200	100

We used hierarchical cluster analysis to identify groups of species that were similar when judged by the amount that their networks overlapped with the networks of other species. We then mapped combined networks for groups of species with high degrees of overlap. Lastly, we quantified the overlap of species and landscape integrity networks by tallying the proportion of each species' network that fell within another species' network or within the landscape integrity network.