Supplementary Material Appendix S1. Glossary of terms.

Centrality – a class of metrics that measures the role of a node in mediating flow between all other nodes in a graph, and identifies 'gatekeeper' nodes that have a relatively large role in facilitating movement across a graph.

Current flow betweenness centrality – a centrality metric derived from circuit theory that treats graphs as conductive surfaces, i.e. networks of nodes connected by resistors. Movement is represented as a process in which random walkers choose to move along edges with probabilities proportional the resistances of those edges. The metric records how often, summed over all node pairs, the node is traversed by a random walk between two other nodes.

Functional connectivity – the degree of movement or flow of individual organisms through the landscape, which is influenced both by their reaction to the the physical arrangement of landscape elements (structural connectivity) and by other factors such as local population dynamics.

Graph – a set of nodes, of which some pairs of nodes are connected by edges. In a valued graph, edges are assigned weights that represent an attribute. In a directed graph, an edge (arc) from node i to j does not imply an edge from j to i. A symmetric directed graph is equivalent to an undirected graph in that all nodes are connected in both directions. In the context of landscape ecology, nodes may represent either habitat patches within a landscape matrix of non-habitat or elements of a landscape lattice. Edges connecting may represent structural or functional connections (e.g., dispersal).

Landscape lattice – a graph derived by overlaying a regular lattice (e.g., of squares or hexagons) on spatially-referenced raster data. Graph nodes are located at the centroid of each element of the lattice, and node attributes are derived from summary statistics (e.g., mean) of the spatial data falling within each element.

Min-cost-max-flow betweenness centrality - a centrality metric based on the concept of maximum flow, the maximum flow feasible between two nodes in a graph given the capacities of all edges. Min-cost-max-flow betweenness centrality is a related metric which first calculates the maximum flow between a pair of nodes, and then the set of edges of minimum cost that permit this maximum flow. The importance of a node is based on the portion of the min-cost-max-flow which must pass through that node, summed over all node pairs.

Network flow analyses – analyses of flow across directed, valued graphs in which edge weights represent flow capacity, and optionally, cost of flow. The analysis obeys capacity constraints (the amount of flow on an edge cannot exceed its capacity), and flow conservation (the amount of flow into a node equals the amount of flow out of it, except when it is a source or sink node).

Shortest-path betweenness centrality – a centrality metric which identifies the one or several shortest (geodesic) paths that connects each pair of nodes on a graph, and counts the number of such shortest paths in which a node participates. The loss of a node that lies on a large proportion of the shortest paths in the network would disproportionately lengthen distances or transit times between nodes. The value attribute of edges can be expressed either as a cost (i.e., of travel along an edge), or as a distance which is inversely proportional to cost.

Appendix S2. Description of conceptual habitat model for gray wolf.

We adapted a previously-published conceptual model that predicted wolf habitat value from data on land cover, primary productivity, slope, and human-associated mortality factors (Carroll et al. 2006). The model extent was the U.S. states of Washington, Oregon, Montana, Idaho, and Wyoming and the southern portions of the Canadian provinces of Alberta and British Columbia. We describe below the data from which these factors were derived and how the factors were combined into a composite habitat suitability index (Figure 2).

LAND COVER

Because abundance estimates of ungulate prey show strong inconsistencies across jurisdictional boundaries, we used land cover and a satellite-imagery-derived metric (tasseled-cap greenness; Carroll et al. 2001) as a surrogate for habitat productivity. We derived land cover types from satellite imagery based data sets (Multi-Resolution Land Characteristics (MRLC) data for the US and MODIS data for Canada)(Homer et al. 2004). The highest value (10) was assigned to deciduous, evergreen, and mixed forest. A value of 8 was assigned to shrubland, grassland, and transitional types. A value of 5 was assigned to rock and sand types. A value of 1 was assigned to snow cover and less-intensive agricultural types (orchards and pastures). Intensive agricultural and urban habitat were given zero value.

PRODUCTIVITY

Within the broad landcover classes described above, prey productivity, and hence wolf habitat value, can be expected to vary widely depending on site productivity. Crist and Cicone (1984) proposed three ‘‘tasseled-cap’’ indices as a standardized means of representing the three principal axes of variation in the values of the six spectral bands used in Landsat Thematic Mapper and the later MODIS sensors. One of the tasselled-cap metrics, greenness, has been frequently used as a ‘‘pseudo-habitat’’ variables due to its correlation with ecological factors such as net primary productivity and green phytomass (Cihlar et al. 1991, Merrill et al. 1993, White et al. 1997), and has proved useful in modeling wildlife distributions (Mace et al. 1999, Carroll et al. 2001). We used an equal-area slice to scale greenness variables derived from summer (July) MODIS imagery to a range of 1 to 1000.

SLOPE

Because wolves are coursing predators that avoid steep terrain, the model also incorporated the negative effect of slope on prey vulnerability (Carroll et al. 2006). Data on wolf distribution data within 4 study areas across Canada showed a power relationship with slope in a univariate regression (P. Paquet, unpublished data). We used the function [index = power(0.965, <slope value in degrees>)] to derive the slope component of the conceptual model from DEM data at a resolution of 90 m. Under this model, habitat with slope of 20 and 40 degrees would have 0.5 and 0.25 the value, respectively, of similar habitat with slope of 0 degrees.

HUMAN-ASSOCIATED MORTALITY FACTORS

Roads and human population are negatively associated with wolf survival in diverse habitats (Fuller et al. 2003). Merrill et al. (1999) developed a 'habitat effectiveness' metric combining road density, local human population density, and interpolated human population density to represent human-associated mortality factors. We used the equation of Merrill et al. (1999) to derive habitat effectiveness from data on roads (1:100,000 resolution USGS and equivalent Canadian datasets) and human population (1990 census data at census block level resolution).

The final composite metric was derived by multiplication of above factors (land cover, greenness, slope, and habitat effectiveness), and then scaled by division by the maximum value/1000 to produce a metric which ranged in value from 1 to 1000.

LITERATURE CITED

Carroll, C., R. F. Noss, and P. C. Paquet. 2001. Carnivores as focal species for conservation planning in the Rocky Mountain region. Ecological Applications 11:961-980.

Carroll, C. M. K. Phillips, C. A. Lopez-Gonzalez, and N. H. Schumaker. 2006. Defining recovery goals and strategies for endangered species: the wolf as a case study. Bioscience 56:25-37.

Cihlar, J., L. St.-Laurent, and J. A. Dyer. 1991. Relation between the normalized difference vegetation index and ecological variables. Remote Sensing of the Environment 35:279–298.

Crist, E. P., and R. C. Cicone. 1984. Application of the tasseled cap concept to simulated thematic mapper data. Photogrammetric Engineering and Remote Sensing 50:343–352.

Fuller T. K.,L. D. Mech, J. F. Cochrane. 2003.Wolf population dynamics. Pages 161–191 in L. D. Mech, L. Boitani, editors. Wolves: Behavior, Ecology, and Conservation. University of Chicago Press, Chicago, Illinois.

Homer, C. C. Huang, L. Yang, B. Wylie, and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. Photogrammetric Engineering and Remote Sensing 70:829-840.

Mace, R. D., J. S. Waller, T. L. Manley, K. Ake, and W. T. Wittinger. 1999. Landscape evaluation of grizzly bear habitat in western Montana. Conservation Biology 13:367–377.

Merrill, E. H., M. K. Bramble-Brodahl, R. W. Marrs, and M. S. Boyce. 1993. Estimation of green herbaceous phytomass from Landsat MSS data in Yellowstone National Park. Journal of Range Management 46:151–157.

Merrill, T., D. J. Mattson, R. G. Wright, and H. B. Quigley. 1999. Defining landscapes suitable for restoration of grizzly bears Ursus arctos in Idaho. Biological Conservation 87:231–248.

White, J. D., S. W. Running, R. Nemani, R. E. Keane, and K. C. Ryan. 1997. Measurement and remote sensing of LAI in Rocky Mountain montane ecosystems. Canadian Journal of Forest Research 27:1714–1727.

Appendix S3. Quantile-quantile regression of centrality metrics reveals that sites with high values of shortest-path betweenness centrality tend to have high values of current flow (a, c) and min-cost-max-flow betweenness centrality (b, d), but the reverse is not true. This suggests that shortest paths are typically subsets of the multiple paths identified by the latter two methods. The slope of the regression line for the 50% quantile (lower line in panel a, not visible in panel b due to proximity to x-axis) is near zero, whereas the slope of the 99% quantile (upper line in panels a and b) is several orders greater in magnitude. Panels c and d plot the slope coefficient against the 100 quantile intervals for panels a and b, respectively.