

LEAST-COST CORRIDOR ANALYSIS FOR EVALUATION OF LYNX HABITAT CONNECTIVITY IN THE MIDDLE ROCKIES

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Abstract

We delineated landscape routes offering the best chance of success for Canada lynx (*Lynx canadensis*) moving among larger, "core patches" of habitat in the Utah-Wyoming Rocky Mountains Ecoregion south of Yellowstone to the San Juan Mountains in the southern Rockies. Using the USGS National Land Cover Database 2001 combined with road density data, we computed a habitat suitability analysis, resulting in potential core habitat areas for lynx. We then generated cost surfaces affecting movement between these core patches based on vegetation type, road density, housing density and slope. We performed a least-cost corridor analysis to locate broad potential corridor routes between core patches. From this first approximation we identified probable movement routes as well as potential barriers and filters where corridor routes intersected with higher-risk habitat. This analysis may be used to identify priority areas for wildlife management to improve the connectivity between core patches for lynx between the northern and southern Rockies.

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Introduction

Habitat loss and fragmentation is generally acknowledged as being a chief factor in the decline of many populations of wildlife throughout the world (Harris 1984, Ehrlich 1986, Lovejoy et al. 1986). Moreover, isolation of small populations is a major concern in the conservation of carnivores (Clark et al. 1996, Noss et al. 1996). To reduce the degree of isolation of fragmented habitat, many conservation biologists have recommended maintaining landscape connectivity by preserving corridors of high value habitat between remaining habitat fragments (e.g. Noss 1983, 1987, Noss and Harris 1986, Craighead et al. 1997, Craighead and Vyse 1995).

Corridors, or landscape linkage zones, have been shown to be helpful in overcoming the effects of habitat fragmentation in a region. They serve to link core areas so individuals can move between them (Mech and Hallett 2001), while also allowing evolutionary and ecological processes (e.g. fire, succession, predation, etc.) to continue operating within an otherwise fragmented system. By ensuring that plants and animals have unsevered connections to other population centers, linkages can prevent or mitigate deleterious population-level effects resulting from isolation - such as inbreeding, low genetic diversity, and extirpation (Noss 1983, Harris 1984, Dobson et al. 1999), and may actually increase the population sizes, viability, and movement of habitat-restricted species (Noss and Cooperrider 1994, Haddad 1999, Haddad and Baum 1999). Landscape linkages should also help to provide for longer-term gene flow among populations in core habitats and linkage areas alike, and should provide a pathway for vegetation communities to shift under regional climate change trends.

While many studies have demonstrated the negative aspects of habitat fragmentation, work examining critical levels of habitat connectivity has not yet come to the forefront of conservation science. For example, while Population Viability Analyses have been conducted for many species, as well as determination of the amount of habitat needed to support a minimum viable population (e.g. Shaffer 1978, 1981, 1987, Gilpin and Soule 1986), few analyses have explicitly demonstrated minimum thresholds of connectivity necessary for viability of a population or meta-population. The scientific debate over the benefits of functional landscape linkages is a reflection of this problem (Simberloff and Abele 1976, Simberloff et al. 1992). However, since habitat fragmentation has been shown to contribute to population declines, it would follow that some degree of habitat connectivity should help ensure long-term viability of species (Noss 1987, 1992, Beier 1993, Noss et al. 1996).

In order to contribute to efforts to identify methods for defining wildlife linkages, we report on our work to delineate best movement corridors for Canada lynx between core patches in the central Rockies of the United States. Using Geographic Information System (GIS) software, and the best available spatial data on habitats and human factors that affect lynx movement, we modeled potential regional-scale travel corridors between core patches of lynx habitat in the southern and northern Rockies. Our results offer a biologically defensible assessment of probable linkage routes for animals traveling from either the northern or southern Rockies into core habitats in Utah and beyond.

These results may be used to direct habitat protection plans of wildlife and land management agencies, as well as conservation planning efforts of other stakeholders, such as conservation organizations. In fact, part of our interest in this effort, and that of our client The Nature Conservancy, was derived from the results of TNC's Utah-Wyoming Rocky Mountains Ecoregional Plan (Noss et al. 2001). This plan included as targets wide-ranging species including lynx, wolf, wolverine, grizzly bear and elk. The Plan broadly identified a wildlife corridor through the Bear River Range, which spans the Utah-Idaho border, but it was too broad a corridor upon which to base a landscape level conservation strategy. This least-

cost corridor analysis is partly an effort to more specifically define this corridor. The lynx was chosen in part based on the assumption that it could largely serve as a surrogate for the wolverine, as the lynx has more specific habitat requirements. It was also chosen because there are now many lynx entering the state of Utah (perhaps for the first time in many years), as a result of the Colorado reintroduction, and many agencies and conservation organizations are interested in where they may settle. Spatial modeling of wolf movement and habitat has already been conducted for this region (Noss et al. 2001, Jones et al. 2004, Switalski et al. 2002).

Methods

Study Area

The study area (Figure 1) includes Yellowstone National Park, and follows the TNC Utah-Wyoming Rocky Mountains Ecoregion boundary (Noss et al. 2001) in its entirety. From the southern tip of the Wind River Mountain Range in Wyoming, the boundary extends southeast, following the continental divide through the Wyoming Basins Ecoregion to join the northernmost part of the Southern Rocky Mountains Ecoregion at the Wyoming-Colorado border. The boundary then follows 5th order watershed boundaries through the heart of the west slope of the Colorado Rockies to join with the San Juan Mountains in southwest Colorado. Care was taken to include the western-most lynx core areas as identified in a previous Colorado analysis (Theobald and Norman 2005). It was important to include the San Juan Mountains in the study area, as this is the current stronghold for lynx that are potential dispersers from the southern Rockies into Utah. From the San Juan Mountains our study area boundary connects to the Utah-Wyoming Rocky Mountains Ecoregion boundary via the Utah High Plateaus Ecoregion.

Current lynx landscape in study area. Currently, lynx reside in both the southern and northern parts of the study area. While the Wyoming range south of Yellowstone has appeared to support a persistent lynx population as evidenced by harvest records from the 1970s and track observations throughout the 1990s (Squires and Oakleaf 2005), the two animals radio collared there in the late 1990's have since died or completely left the area (personal communication, John Squires, USFS Rocky Mountain Research Station). Hair snag stations for lynx in Yellowstone Park in the last decade have produced very little evidence of either a local population in the Park or dispersers coming into the Park from other areas in the northern Rockies (personal communication, John Squires). However, there are currently about eight collared lynx in the Greater Yellowstone region that have dispersed there from the introduced population in Colorado (personal communication, John Squires).

There is a fairly healthy population of lynx in the Colorado Rockies at the southern end of the study area, thanks to a reintroduction effort undertaken by the Colorado Division of Wildlife Resources (CDOW), in which 218 lynx were reintroduced into southwestern Colorado starting in 2001. As of the most recent reporting on the population by CDOW (Shenk 2007), the population of lynx in the Colorado Rockies currently may number as many as 120 animals. CDOW is currently tracking 71 of the 120 reintroduced lynx still possibly alive. There are 49 animals from which CDOW has not heard signals since at least July 1, 2006 and CDOW considers these animals to be "missing." GPS monitoring of this new population indicates that the animals primarily use high elevation forested areas, with most movements away from the core release area trending to the north. The tracked Colorado lynx that have crossed through our study area in Utah to locations west and north have traveled to the central Wasatch Plateau of Utah, to the north end of the Book Cliffs in northern Utah, and over the Wasatch Plateau west of Cedar City (and in the case of one animal, clear out to Nevada) (personal communication Kevin Bunnell, Utah Division of Wildlife Resources, personal communication with Tanya Shenk, CDOW).

Replace this page with Fig 1 – STUDY AREA BOUNDARY

Determining core areas for lynx

Using 90m-cell resolution, we completed a habitat suitability analysis to identify best core areas for lynx in the study area. Inputs were vegetation community types (National Land Cover Database 2001), and weighted road density (Census 2000 TIGER/Line data). Each cell was attributed with a score based on the dominant vegetation community type from the reclass values in table 1. Vegetation types (Figure 2) were assigned scores from 1 to 10 based on known lynx affinities for various land cover types, and reclassified in a binary raster where scores of 8, 9 and 10 were considered to contain suitable vegetation types for lynx (Ruediger et al. 2000, Singleton et al. 2001, Singleton et al. 2002, USFS 2002, Bunnell et al. 2005, Wasatch-Cache National Forest 2005, Southwest ReGAP model, 2006). Suitable road density (Figure 3) for lynx was similarly calculated in ArcGIS using a kernel line density function, and assessed in a binary manner, with values below our 6.4-km/0.9-km radius circle ($<4\text{-mi/mi}^2$) threshold considered acceptable as core (Singleton et al. 2001). After all cells that surpassed both the vegetation suitability and road density suitability thresholds were identified, habitat patches were formed using ArcGIS REGIONGROUP, 8-neighbor. For the purposes of this model, we considered large enough core patches for lynx to be those that are at least 1,600 km², the approximate area of eight average home range sizes for male lynx in the American Rockies (Ruggiero et al. 1999, Squires 2005, Shenk 2006, personal communication John Squires, personal communication Tanya Shenk). This generated nine individual core habitat areas within the study area (Figure 4).

Table 1. Land cover permeability scores.

<u>Land Cover Class</u>	<u>Score</u>
Water	1
Bare Ground	2
Ice/Snow	3
Urban/Developed	1
Grassland/Developed Open Space	2
Agriculture	1
Deciduous Forest	8
Evergreen/Mixed Forest	10
Woody Wetlands/Riparian	7
Emergent Herbaceous Wetlands	3
Shrub/Scrub	4

We assumed that areas identified as core patches in our model would be of sufficient area to support more than two mated-pairs of lynx to reside year round, for multiple years; that core patches would provide necessary land cover types for denning and hunting; that cores would contain necessary prey to support lynx year-round; and that core patches would provide sufficient safety from human persecution. We also assumed that movement corridors identified in our model would provide the habitat and security necessary to safely travel between core patches, while providing adequate thermal and prey resources during the journey.

Permeability Layer

The permeability layer represents the relative ease with which an individual lynx can travel through the landscape. It is derived by combining land cover, housing density, road density and percent slope layers (discussed below), each of which are assigned a score that represents each components' degree of permeability to traveling lynx.

Replace this page with Fig 2 – LAND COVER

Replace this page with Fig 3 – WEIGHTED ROAD DENSITY

Replace this page with Fig 4 – CORE HABITAT AREAS

Vegetation type. We used the same scoring system for determining inter-core habitat permeability as we used to determine core habitat suitability (see Table 1). The decision to treat both potential core and movement habitat vegetation scores the same way was derived from lynx tracking data from the northern Rockies that found that lynx were selecting conifers for long distance travel routes and dispersal (personal communication, John Squires).

Housing density. In our model, the density of housing (Figure 5) was used to represent human settlement impacts (and other, concomitant human impacts) to the efficacy of lynx movement between patches. We evaluated private lands only, assuming that housing density will be negligible on public land (all public lands were assigned a score of 10). Using 2000 Census block group data, we calculated housing density/km² as follows:

$$[\text{House_density}] = [\text{Housing Units}] / [\text{Area in km}^2]$$

We reclassified this raster in a 90m-resolution grid using the scoring system in Table 2, the same scoring system that Singleton et al. (2001, 2002) used for their lynx LCP model in the Pacific Northwest:

Table 2. Housing density permeability scores.

Houses/km²	Score
0 – 65	10
65 – 130	8
130 – 260	5
> 260	1

Road density. We used Census 2000 TIGER/Line data to calculate road density across our study area (Figure 3). While TIGER/Line data is known to have coding and geometrical errors, we did not edit the data for the sake of maintaining the uniformity of the dataset. The below road classes are based on the Census Feature Class Codes (CFCC) assigned by the Census Bureau. To allow for primitive roads to be counted once, secondary roads twice, and primary roads five times, road types were weighted accordingly:

Table 3. Road weights applied to calculate road density.

Road Class	Weight
Primary, un-separated	5
Primary, separated	2.5
Secondary	2
Primitive/Rural/Trails	1
Primitive, separated	0.5

In the raw TIGER data, roads with separated lanes are classified as a separate road type. In this model, these were assigned a score of half the value of a non-separated road. Examples of primary roads include freeways, while secondary roads are largely state and county highways. The scoring system was derived based on the expert opinion of our peer review team:

Replace this page with Fig 5 – HOUSING DENSITY

Table 4. Weighted road density permeability scores.

Km/km²	Score
0 – 2.5	10
2.5 – 6.2	8
6.2 – 30	1

Slope. Topography in the study area is depicted in Figure 6. Current lynx movement studies indicate that lynx prefer gentler slope (personal communication, John Squires). For example, the most recent data available for the Colorado lynx population indicates that lynx typically use slopes with an average of about 15° (Shenk 2007). We derived slope in degrees from USGS National Elevation Dataset, 90-m resolution, and used the same scoring system as Singleton et al. (2001, 2002) such that:

Table 5. Slope permeability scores.

Degree Slope	Value
0 – 20	10
20 - 40	8
> 40	6

The final permeability layer seen in Figure 7 was created by multiplying the four component layers together and then transforming the results to the scale of 0.1 – 1.0 for each cell so that:

$$[\text{lynx_perm}] = ([\text{lynx_veg}] * [\text{lynx_housed}] * [\text{lynx_rddens}] * [\text{lynx_slope}]) / 10,000$$

Our expert peer review team agreed that equal weighting of the four elements (vegetation type, housing density, road density, and slope) was appropriate for this study area. Depending on what factors dominate other regions where lynx least-cost corridor analyses are being calculated (for example, the Northeast), certain factors such as housing density might be weighted slightly higher (personal communication, Dave Theobald, Natural Resource Ecology Laboratory, Colorado State University).

Cost Distance and Corridor Analyses

Finally, permeability as a probability function was transformed into a weighted cost function that represents the penalty to be applied during a cost distance analysis (and during movement from one core area to another). As the permeability decreases, it costs the dispersing individual more to cross the cell, and this cost is represented as additional distance (Fink 2005). We used a linear weighted cost distance function (based on Singleton et al. 2001, 2002), such that, when combined with the cell width (90m in our case), values range from actual cell width of 90 meters (no penalty to cross) to 100x cell width (large penalty to cross). We calculated the weighted cost function (lynx_wcf)grid as:

$$\text{lynx_wcf} = 90 * (100 - (100 * [\text{lynx_perm}]))$$

The costdistance function in ArcGRID combines the lynx_wcf (weighted cost function) layer with each core habitat area to generate a total of nine cost distance grids, one per core habitat area, in the following manner:

$$\text{cd_corex} = \text{costdistance}(\text{corex}, \text{lynx_wcf})$$

where x = 1-9

Replace this page with Fig 6 - SLOPE

Replace this page with Fig 7 - PERMEABILITY

To complete the analysis, the cost distance grids were then analyzed in meaningful pair-wise combinations using the corridor function in ArcGRID in order to derive the least-cost corridor between those pairs of core areas (Fink 2005).

$(core_x)_(core_y) = \text{corridor}(cd(core_x), cd(core_y))$

The corridor outputs do not represent linear distance; rather they contain a wide range of values in weighted meters, representing the cost (in distance) to a dispersing individual as it moves throughout the landscape. It is assumed that increasing weighted distance means diminished likelihood of successful inter-core dispersal, and that the least-cost corridor is the predicted path that will allow for the easiest dispersal (Fink 2005).

Results

Our model indicated that there are nine clusters of relatively well-connected blocks of suitable landscapes of sufficient size to be considered core lynx habitat (Figure 4). These habitat concentration areas included the High Uintas Wilderness (plus adjacent forested lands), a core patch in the Bear River Range, and many core patches in close proximity to one another in both the west slope of the Colorado Rockies and the greater Yellowstone region.

Figure 7 portrays the results of the landscape permeability analysis for lynx traveling throughout the study area. Green areas represent the most permeable lands in terms of suitable vegetation, gentler slope and less human and road impacts. Yellow represents moderate permeability, and shades of red illustrate the least permeable regions of the study area.

Results of the least-cost corridor analysis (Figure 8) depict three key corridors linking the lynx core patches in the study area. The movement corridors represent the least cost to an individual lynx when choosing a pathway between point a and b (in this case, between core patches). The corridors include, from north to south, one linkage between the Wyoming Range core and the Bear River Range core through southeast Idaho, a small linkage between the Bear River core and the Uintas core, and one linkage to connect the southern Rockies with the Uintas Core. This path connects the Flat Tops core via the high country along and north of the Yampa River to connect to the Uinta core in extreme northeast Utah.

These three pathways represent the greatest likelihood of successful lynx crossing between lynx core patches, based on our initial assumptions that lynx tend to select coniferous habitats and gentler slopes for general movement. Lower likelihood of human disturbance during the journey should occur on the least-cost corridors, since they go through areas of lowest human population density and lowest road density. That said, there are a few places within corridors and between adjacent cores where potential barriers to movement exist. This would likely include the I-80 crossing in the small corridor between the Uintas and the Bear River Range Core, and both I-70 and the Colorado River between the Maroon Bells and Flat Tops core (though the CDOW lynx satellite tracking data do show that at least one individual has made this crossing). There are also a few State highways that would be crossed during corridor travel, although these probably present less of a barrier to lynx. These crossings include both Highways 30 and 89 through the corridor that connects the Bear River Range Core with the Wyoming Range and Teton cores, and the 191 and Hwy 40 crossings within the corridors that connect the southern Rockies with the Uintas core.

Insert fig 8 here – CORRIDORS

The majority of the least-cost pathways, and lynx core areas, in the model traverse areas that are predominately public land. However, the situation is a little bit different in northeast Utah (see Utah land ownership in Figure 9). Unlike most of the other cores in the model, the Bear River Range core in northeastern Utah is predominantly private land. And the least-cost corridor between this core and the Uintas core is virtually entirely comprised of private land.

Discussion

Lynx movement data recently acquired through radio and GPS-collared lynx in both Wyoming and Colorado have shed light on the likelihood of whether lynx will use, and indeed whether they have already been using, the corridors and core patches identified in this model. Partly because there are very few “local lynx” (originating in Montana, Idaho or Wyoming) known to currently inhabit the northern part of the study area that includes the Yellowstone region, very little is published on their known movement and dispersal patterns.

The GPS and radio collar data recently released by Colorado Division of Wildlife for the reintroduced Colorado lynx population give a robust data set for initial lynx movements within the Colorado Rockies and between the Colorado Rockies and middle and northern Rockies (Shenk 2007). These data indicate extensive movement of lynx virtually throughout the West slope of Colorado, including core patches identified in our model, and with particular affinities along the continental divide (and extending into both Wyoming and New Mexico). The CDOW data indicate a substantial cluster of lynx locations in the Uintas, and up and down the Wasatch Plateau in Utah. The CDOW findings also show that seven or eight of the Colorado lynx are now residing in the Greater Yellowstone Ecoregion (also personal communication, John Squires). Pathways these lynx traveled to get there include not only the one identified in our model (through the Uintas and Bear River Range to the Wyoming Range), but others that include the Powder Rim linking the northern tip of the Southern Rockies to the Wind River Range, and at least one animal that crossed the Red Desert in southwest Wyoming.

The findings of our least-cost corridor model for lynx have relevance for the wildlife and habitat programs of state and federal agencies, as well as conservation organizations working in the middle Rockies region. In particular, The Nature Conservancy should find utility for this model in its conservation programs in the Utah-Wyoming Rocky Mountains Ecoregion. Figure 10 depicts our lynx least-cost corridor analysis overlaid with TNC’s portfolio sites in the Utah-Wyoming Rocky Mountains Ecoregional Plan. In particular, areas where lynx core patches and least-cost corridors overlap with portfolio sites would be excellent places for TNC to focus conservation resources. While the bulk of the Bear River Range core and the corridor south of that are on private land, TNC has many effective strategies for promoting proactive management and land preservation on private lands. In fact it is already implementing such strategies in the region; one key example is the Selman Ranch in the Bear River Range area.

Insert fig 9 here – UTAH LAND STATUS

Insert fig10 here – TNC CORRIDOR/PORTFOLIO SITES OVERLAY

The least-cost corridor assessment for lynx movement in North America is still a science in flux; few researchers have attempted large-scale habitat modeling for predicting long-distance lynx movement. When we began this effort, very little information existed in terms of known lynx dispersal tendencies and routes used on the ground in the American Rockies. Since we have completed our model, tracking data for the Colorado lynx population has become available. The data so far show that some of these animals are exhibiting aberrant behavior in that they are crossing large distances of habitat heretofore considered improbable for lynx (i.e. large sagebrush tracts). They have also been documented readily crossing roads. As more data comes available, future iterations of our model might be run with relaxed road weighting or vegetation parameters in inter-core habitat to reflect the interesting travel routes chosen by some of the Colorado animals. However, even the preliminary data show that when the lynx stop moving they are typically in conifer zones generally associated in the literature with suitable lynx habitat (i.e. spruce/fir forests), so we would not recommend any changes to the core habitat parameters in any future iterations of this model.

The results of this analysis represent the probability of successful dispersal for lynx between core habitat areas, but it is important to note that this model has the distinct advantage of assessing the entire landscape at once, while an animal traveling on the ground may not have prior knowledge of the territory it is crossing or obstacles it may come upon. Still, based on best known published literature on habitat affinities for lynx, and current on-the-ground movement data for lynx in the northern and southern Rockies, this model represents a best guess for likely pathways to be used by lynx between core patches in the middle Rockies. As this model is based on landscape scale datasets, it is suitable for making conservation and management decisions on a landscape scale as well. This includes not only land resource plans such as Forest Plans, but also decisions on how to treat or manage individual land management units such as TNC portfolio sites that, if better managed or conserved, can help create a network of protected landscape linkages on the ground, for the benefit of many large and wide-ranging forest species.

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Appendix 1: Base Map Metadata

All analysis was done in Windows XP Pro environment using Arc/INFO 9.1.

Digital data were gathered from various sources for purposes of this project, which are summarized below, including any major processing steps required. All analyses were completed using a cell size of 90 meters. All data were collected and re-projected to Albers projection:

Projection ALBERS
Datum NAD83
Units METERS
Spheroid GRS1980

Parameters:

1 st standard parallel	39 30 0.000
2 nd standard parallel	43 30 0.000
central meridian	-109 0 0.000
latitude of projection's origin	36 0 0.000
false easting (meters)	600000.00000
false northing (meters)	0.00000

Digital Elevation Model (Slope)

Elevation data were used to generate the slope surface used in lynx costdistance and corridor modeling. A study-area wide raster was generated by mosaicing the DEM together.

Title: National Elevation Dataset

Publication date: 1999

Source: U.S. Geological Survey (USGS), EROS Data Center

<http://gisdata.usgs.net/ned>

Mapping scale: 90-m cell size

Housing Density

Census Block Groups were downloaded as zip files per county, per state. Housing density on private lands was calculated by combining census block group data with land ownership maps, producing housing units per square kilometer on private lands. To score the data, we treated public lands as having a suitable, or low, score, based on the assumption that housing on public land is virtually non-existent. Data was derived from 1:100,000 scale land ownership maps, and used in lynx costdistance and corridor modeling.

Title: TIGER/Line Files, Census 2000

Publication Date: 2001

Source: U.S. Census Bureau

http://arcdata.esri.com/data/tiger2000/tiger_download.cfm

-Block Groups 2000

Mapping Scale: 1:100,000

Roads

Road data were compiled from Census 2000 TIGER/Line files. Data were downloaded as zip files per county, per state. Each state was mosaiced together individually, then the five resulting state shapefiles were mosaiced into 1 shapefile covering the entire study area. Using a 900-m radius (1 mile²) circle, a kernel line density function was computed. The resulting weighted road density was used in lynx

costdistance and corridor modeling. It was also re-classified into a binary dataset combined with vegetation data to generate core habitat areas, with values below 4 mi/mi² considered acceptable as core habitat.

Title: TIGER/Line Files, Census 2000

Publication Date: 2001

Source: U.S. Census Bureau

(http://arcdata.esri.com/data/tiger2000/tiger_download.cfm)

-Line features - Roads

Mapping Scale: 1:100,000

Vegetation

Vegetation data were used both to generate core habitat areas and in the lynx costdistance and corridor modeling process. Data were obtained in multiple zones, mosaiced into 1 dataset and re-sampled to 90-m cell size.

Title: National Land Cover Database 2001

Publication Date: 2003

Source: U.S. Geological Survey

(<http://www.mrlc.gov>)

Mapping scale: 30-m cell size; re-sampled to 90-m cell size