MEXICAN WOLF RECOVERY: HABITAT SUITABILITY AND DISPERSAL POTENTIAL

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ABSTRACT:

For the first time since 1982, the United States Fish and Wildlife Service (FWS) is updating Mexican Gray Wolf Recovery Plan. In order to provide comprehensive recommendations regarding the conservation of this species, potential habitat must be delineated throughout its historic range. Assessments of favorable habitat, dispersal potential, and reintroduction feasibility have been published for the Pacific Northwest, the northeastern U.S., the Great Lakes, and the northern Rockies. Such projects provide a strong methodological foundation for developing analogous research for Mexican wolves in the Southwest, where relatively few studies have taken place.

The purpose of this study was to aid the FWS in its efforts by completing a spatial analysis of favorable Mexican wolf habitat and connectivity potential. With the use of a geographic information system, habitat models were developed and tested within the Mexican Gray Wolf Experimental Population Area. Results from this analysis were then extrapolated to the majority of the Mexican gray wolf's historic range, encompassing New Mexico, Arizona, Utah and Colorado.

Based on a literature review of landscape attributes observed to influence wolf habitat selection and mortality, the following variables were selected to model wolf habitat: land cover type, elevation, distance from roads, human density, and distance from ranching operations. Patches of viable habitat were identified and connectivity between them was analyzed. The results of this analysis present 181,584 km^2 of suitable Mexican wolf habitat throughout the four-state region. The largest patch comprises 23,202 km^2 of land (approximately 30% of which is currently protected as designated Wilderness Area, National Forest, or State Forest). This area alone is most likely capable of supporting 240-480 individuals.

Five of the largest habitat patches identified are functionally connected through a network of corridors. Deforestation and anthropogenic encroachment are endangering one of these essential linkages, posing a threat to future wolf dispersal into southern Colorado. Based on this study's results and conclusions, recommendations were provided to the FWS to aid in the development of realistic recovery goals and the investigation of possible reintroduction sites for Mexican gray wolves.

Table of Contents:

List of Tables:

List of Figures:

Introduction:

Wolf Biology

The Mexican gray wolf (*Canis lupus baileyi*) is the most rare and genetically unique subspecies of gray wolf (*Canis lupus*) occurring in the United States. Commonly referred to as lobos, Mexican wolves came by their namesake due to their unique ability to flourish in rugged southwestern terrain. *C. l. baileyi* ranged much further south than any other wolf subspecies in North America, inhabiting lands throughout central Mexico, Arizona, New Mexico, southwestern Texas and western Oklahoma. It is now thought that this range extended further north than previously believed, reaching into southern Colorado and Utah.

As a relatively small subspecies, the Mexican wolf weighs approximately 50-80 pounds and stretches from about 1.5 to 2 m in length. The Rocky Mountain gray wolf (*C. l. irremotus*) to the north, on the other hand, is approximately the same length but ranges in weight from 80 to 100 pounds. While typical coloration for a Rocky Mountain gray wolf ranges from white to black, Mexican wolf coloration is a combination of gray, tan, buff, and black, but never solid black or white like many other wolf species (USFWS 2010). Despite many phenotypical differences, Mexican wolves have a similar social structure to other gray wolves, with pack sizes ranging from 4 to 8 individuals and containing only one dominant pair. The alpha pair is typically monogamous and is the only pair that breed within a pack.

Like all wolf species, Mexican wolves are very wide-ranging, with average pack home ranges varying between 390 to 650 km^2 (AZGFD). Mexican wolves are also highly adaptable, capable of surviving in a broad variety of habitat types

(Weaver et al. 1996). They prefer high elevations and forest cover, but can exist in shrubland and other harsh land cover types. As a generalist species, Mexican wolves are flexible regarding their prey of choice (J. Oakleaf, personal communication). Depending on their surroundings, they will hunt anything from elk, mule deer, and white-tailed deer to javelina, rabbits, and other small mammals (USFWS 2010). The unique biological and ecological characteristics of the Mexican wolf make it unlikely that its range would ever overlap with that of *C. l. irremotus* to the north or any other subspecies. This promotes the evolutionary independence of *C. l. baileyi* and diminishes the possibility of hybridization.

<u>Problem Statement and Project Objectives</u>

Government control measures and public animosity toward Mexican gray wolves (*Canis lupus baileyi*) caused this species to be functionally eradicated from its historic range in the southwestern United States before 1970. They were listed under the Endangered Species Act in 1976, inciting the creation of a Mexican Wolf Recovery Team under the U.S. Fish and Wildlife Service (FWS). This team of experts was tasked with developing strategies for the species' conservation, despite uncertainty at the time regarding the political and biological feasibility of Mexican wolf reintroduction and persistence. By the following year, five of the few remaining Mexican wolves were caught in Mexico for the purposes of a bi-national captive breeding program, initiated in conjunction with the United States. In 1982, the recovery team finished writing the Mexican Wolf Recovery Plan, which required the maintenance of this captive breeding program and the establishment of a self-sustaining, free-ranging population of at least 100 wolves (USFWS 2010).

Given the anti-government sentiments and reliance on livestock ranching throughout this region of the country, it is not surprising that there were several setbacks and lawsuits throughout this process, but the project finally came to fruition in 1998. In that year, the FWS cleared the initial release of 11 Mexican wolves into the Blue Range Wolf Recovery Area (BRWRA) of eastern Arizona in an effort to reestablish free-ranging wolf packs. Additional releases occurred each year until 2004, and then again in 2006 and 2008, leading to the release of 92 individual wolves in total (USFWS 2010). Populations were relatively successful, producing the first wolf pup born in the wild in over 50 years shortly after release. Only two years after the first release took place, approximately 10-18 of these wolves were captured from the Arizona recovery area and translocated into the Gila National Forest in New Mexico (USFWS 2010). Since that time, several Apache tribes have also entered into cooperative agreements with the FWS for the purposes of monitoring wolf populations.

In 2005, the five-year review for the Blue Range reintroduction project was submitted to the FWS. It included 37 recommendations for improving the survival of free-ranging wolves (USFWS 2010). Scientists monitoring wolf populations throughout the recovery areas in Arizona and New Mexico counted only 42 Mexican wolves in 2009, and estimated around 50 individuals in 2010 (USFWS 2010). Causes of death have varied over the years, but 2008 claimed the highest number of wolves killed by humans since the initiation of the recovery program. Illegal shooting is a critical factor when it comes to wolf mortality in the Southwest. Six of the thirteen wolves killed in 2008 were a result of such an incident (USFWS 2010). In fact, 46%

of total wolf deaths between 1998 and 2010 have been due to illegal shooting, and at least 61% have been caused by interactions with humans (vehicle collision and potential "other" causes of death such as legal shooting and trapping, Table 1).

Table 1: Mexican Wolf Mortality Statistics (data acquired from USFWS website, 3/28/2011)

Data Current as of 31 December 2010

Year	Illegal shooting	Vehicle collision	Natural[a]	Other[b]	Unknown	Awaiting necropsy	Total
1998	4	0	0	1	0	0	5
1999	0	1	2	0	0	0	3
2000	1	2	1	0	0	0	4
2001	4	1	2	1	1	0	9
2002	3	0	0	0	0	0	3
2003	7	4	0	0	1	0	12
2004	1	1	1	0	0	0	3
2005	3	0	0	0	1	0	4
2006	1	1	1	1	2	0	6
2007	1	0	1	0	2	0	4
2008	6	2	2	1	2	0	13
2009	4	0	3	0	0	1	8
2010	2	0	1	0	0	3	6
Total	**37**	**12**	**14**	**4**	**9**	**4**	**80**

[a]Natural causes of death may include, but are not limited to predation, starvation, interspecific strife, and disease.

[b]Other causes of death may include, but are not limited to capture-related mortalities, legal public shooting, and public trap related mortality.

On February 22nd of this year, the FWS Southwest Region's new Mexican Wolf Recovery Team gathered for the first time (USFWS Press Release 2011). The team will be revising the Mexican Wolf Recovery Plan over the next two years, an important aspect of which will be the development of specific criteria for recovering and delisting the species in the future. The original goals are now outdated. They were written in absence of scientific or field data regarding the species' ability to persist under reintroduction scenarios, and with little hope that the population could ever be restored to numbers suitable for delisting (J. Oakleaf, personal communication). Mexican wolf population numbers are dangerously low, but strategic, conservation-oriented recovery goals could act as a stepping-stone toward Mexican wolf restoration. A large-scale spatial analysis of wolf habitat availability and connectivity has not been completed for this region of the country. Given the possibility of additional reintroductions in the future, information on suitable wolf habitat throughout the Southwest would be helpful in directing recovery efforts to areas that are capable of supporting wolf populations (Dr. John Oakleaf, personal communication). The goal of this study, therefore, is to predict the geographic distribution of favorable wolf habitat throughout a four-state region and analyze connectivity potential between identified areas of habitat. The outcomes and recommendations resulting from this analysis will hopefully inform decisions throughout the recovery goal development process, leading to the identification of future reintroduction sites for Mexican wolves and the prioritization of critical lands for conservation.

Factors Influencing Wolf Habitat Favorability

There is a long history of persecution against wolves in general, and the Mexican wolf specifically. As a result, the majority of wolf mortality is due to conflict with humans (Mech and Goyal 1993, Mladenoff et al. 1995). Whether due to direct killings or an adapted behavioral aversion, wolves are not found in areas where the concentration of human developments (such as roads or towns) is high (Fuller et al. 1992, Mech and Goyal 1993). Although the wolf's reproductive biology and flexible social structure make it one of the most ecologically resilient large carnivores

(Weaver et al. 1996), it is clear that sizeable areas of high-quality, secure habitat will be required in order for the species to thrive in the Southwest.

Land use and land cover play an important role in predicting wolf habitat. In the Great Lakes region, Mladenoff et al. (1995) found that gray wolf (*Canis lupus*) pack territories had much greater proportions of mixed conifer-hardwood forest, forested wetlands, and public-owned lands than non-use areas did. Conversely, they discovered that pack areas had much lower proportions of agricultural lands, lakes, and mixed-ownership private lands than surrounding non-use areas. These findings were corroborated in later studies that resulted in similar findings (Mladenoff and Sickley 1998, Mladenoff et al. 1999). In the Northern Rocky Mountains, Oakleaf et al. (2006) found of the variables examined, forest cover and prey density were the most highly correlated with wolf presence, while livestock density and human density were correlated with wolf absence. Dispersing wolves display comparable behavior, selecting for natural land cover types and avoiding areas influenced by human modification (Treves 2009). In a different vein, Carroll et al. (2003) performed a study in the Rocky Mountains using vegetation, climate, topography, and MODIS-derived metrics. They found that favorable habitat was often associated with MODIS “tasseled-cap greenness”, elk density, and public parklands, while negatively correlated with variables like slope. Boitani (2003) and Houts (2000) have also both shown that forest cover is a significant factor in determining wolf habitat.

Many studies have analyzed critical road density thresholds for wolf habitat. Such studies have resulted in estimates of 0.45 or 0.58 km of linear road per km^2 as the maximum road density inhabitable by wolves (Fuller et al 1992, Mladenoff et al 1995). Others have reported results as an average of 0.15, 0.36, or 0.12km/km^2 (Mech 1988, Mladenoff 1995, Oakleaf et al. 2006). Thiel (1985) added that wolf breeding/denning is isolated to areas with road densities no higher than 0.59 km/km^2. In a 1988 study, Mech et al found that wolves will inhabit an area with a road density as high as 0.73 km/km^2 as long as it is bordered by wolf habitat with very little human influence. While it is true that wolves typically avoid roads due to the presence of humans and not due to the roads themselves, road density has been identified as one of the most significant factors in predicting wolf presence (Fuller et al 1992, Larsen and Ripple 2006, Mladenoff et al 1995).

Human density has also proven to be an important variable in wolf habitat modeling. Fuller et al (1992) discovered that 88% of wolf packs in Minnesota resided in areas with no more than 8 humans per km^2. In studies throughout the Great Lakes region, Mladenoff et al (1995) and Mladenoff and Sickley (1998) found that wolf distribution was maintained in areas with less than 1.54 and 1.52 humans per km^2 respectively. In addition, recent findings suggest that human density levels tolerated by wolves may vary depending on proximal road densities (Carroll et al. 2003).

Factors Influencing Wolf Habitat Connectivity

Connectivity between isolated areas of fragmented habitat is a growing field of research. It has long been identified as a key area of conservation research and management. Connectivity analyses are critical for a number of reasons. In the short-term, isolated habitat patches cannot support the inter-specific population dynamics of an ecosystem or meet the needs of area-sensitive species (Harrison 1994). In the long-term, an isolated area of habitat will constrain genetic diversity, undermine evolutionary processes, and obstruct species from shifting their ranges in response to climate change (Frankel and Soule 1981).

There have been a number of different methodologies used to model connectivity for wolves. Harrison and Chapin (1998) used a geographic information system (ARC/INFO) to analyze habitat viability and corridors between the northeastern U.S. and southeastern Canada, incorporating environmental variables such as land cover, human density, road density, and wolf demographic data. Quinby et al. (2000) performed a successful least-cost path analysis between Algonquin Provincial Park in Ontario and Adirondack Park in New York. This study was further validated by Carroll (2003). Carroll et al. (2002) successfully modeled connectivity along a highway between southeastern British Columbia and southwestern Alberta (Canada) using a Spatially Explicit Population Model (SEPM) called PATCH. Using the same tool, connectivity throughout the landscape matrix of the Yellowstone-to-Yukon region was analyzed for both wolves and grizzly bears (Carroll 2004).

Although the potential for connectivity existed in each of the areas studied above, several researchers noted the importance of large, viable areas of habitat for both source and destination patches (Harrison and Chapin 1998, Harrison and Bruna 1999). Although a corridor may link two potential areas of habitat, the influence of edge effects and changes in ecosystem dynamics on isolated patches has impacts beyond our current understanding. That said, wolves have been known to disperse up to 886 km (Fritts 1983) and the average distance covered by "long-distance" dispersers was 264 km in Montana (Wydeven et al. 1998). Wolves have rarely been known to travel across extensive areas of farmland and rangeland (Wydeven 1998). They have dispersed across icy lakes, four-lane highways, areas of high road density, and large swaths of non-habitat, but typically circumvent areas of human development (Harrison and Chapin 1998). Mountainous terrain has facilitated recolonization by dispersers in several cases (Wydeven et al. 1998).

Materials and methods:

The first step in this analysis was to model suitable Mexican wolf habitat using two different methods. These models were based on variables recommended from the literature regarding wolf habitat favorability. Habitat patches from the selected modeling approach were then derived and a threat analysis based on distance from roads and ranches was completed for the resulting patches. Finally, corridor analyses were performed between critical areas of suitable Mexican wolf habitat.

Study Area

The original area of focus for this project was the Mexican Gray Wolf Experimental Population Area, as designated by the FWS. It stretches across approximately 311,220 km^2 of Arizona and New Mexico, enveloping the Blue Range Wolf Recovery Area, Fort Apache Indian Reservation, San Carlos Apache Indian Reservation and parts of Albuquerque, El Paso, Flagstaff, Phoenix, and Tucson. Major land cover types in this area, as classified by the National Land Cover Dataset (MRLC NLCD, Xian et al. 2009), include evergreen forest (17%), shrub/scrub land (59%), and grassland (18%). See Table 2 for more details. Elevations range from 78 to 3,631 m. Human population densities are very low throughout most of the area (minimum of 0.02 humans per km^2) but peak in the population centers (maximum of 3,255 humans per km^2). See Figure 1 for an overview of this study area.

In order for this project to be of more relevance to the FWS, the geospatial habitat models developed in the Experimental Population Area were expanded to an area encompassing the majority of the Mexican wolf's historic range in the U.S. This larger study area included all of Arizona, Colorado, New Mexico, and Utah. The four-state area has similar landscape characteristics to the study area described above, being typical of southwestern habitats. Major land cover types remain the same, with evergreen forest comprising approximately 17% of total land area, shrubland comprising 48%, and grassland comprising about 20% (Table 2). Maximum elevation in this region increases to 491,514 m. Human population density throughout this area is very similar to the smaller study area as well, ranging from 0 to 3,515 people per km^2. Again, high-density regions remain constrained to large population centers. According to Geographic Names Information System data, there are approximately 3,891 ranches spread throughout this four-state region. See Figure 4 for an overview of this region.

Table 2: Land Cover Classifications and Percent of Total Area

Experimental Study Area: Land Cover Data			Four-state Study Area: Land Cover Data		
Land Cover Type	**Area (km^2)**	**Percent Total**	**Land Cover Type**	**Area (km^2)**	**Percent Total**
Open water	53.76	0.17	Open Water	7724.15	0.70
Perennial snow/ice	N/A	N/A	Perennial snow/ice	656.17	0.06
Developed, open space	325.28	1.05	Developed, open space	12107.35	1.10
Developed, low intensity	191.90	0.62	Developed, low intensity	6194.28	0.56
Developed, medium intensity	95.44	0.31	Developed, medium intensity	2600.38	0.24
Developed, high intensity	15.85	0.05	Developed, high intensity	597.67	0.05
Barren land	325.06	1.04	Barren land	38753.45	3.51
Deciduous forest	19.34	0.06	Deciduous forest	32363.78	2.94
Evergreen forest	5401.42	17.36	Evergreen forest	192771.32	17.48
Mixed forest	0.85	0.00	Mixed forest	3545.11	0.32
Shrub/scrub	18227.13	58.57	Shrub/scrub	524889.54	47.60
Grassland/herbaceous	5749.67	18.47	Grassland/herbaceous	215403.32	19.54
Pasture/hay	72.04	0.23	Pasture/hay	13708.68	1.24
Cultivated crops	549.53	1.77	Cultivated crops	43172.04	3.92
Woody wetlands	65.30	0.21	Woody wetlands	5467.40	0.50
Emergent herbaceous wetlands	29.38	0.09	Emergent herbaceous wetlands	2636.30	0.24

Data

John Oakleaf of the FWS provided pack range data for this project. Range shapefiles were created using 95% (home range area) and 50% (core area) fixed kernel methods on field data collected from radio-collared wolf packs monitored between 1998 and 2009. Unless otherwise noted, all data used for analyses in the Experimental Population Area were downloaded in 30m resolution. Once the study area was expanded to a four-state region, data used for analyses were downloaded in 90m resolution for the purpose of more efficient processing. Multi-Resolution Land Characteristics Consortium (MRLC) land cover and percent canopy products were downloaded from the USGS seamless server (MRLC NLCD, Xian et al. 2009). A Digital Elevation Model (USGS NED) of each study area was obtained from the USGS seamless server as well, while state and county boundaries were acquired from the Database of Global Administrative Areas (GADM). The Southwest Regional Gap Analysis data was downloaded from the USGS National Biological Information

Infrastructure site (30m USGS NBII). Ranch location points were extracted from the Geographic Names Information System (USGS GNIS 2011). Population density data were downloaded for the U.S. from CIESIN (1km) and clipped to the proper extent. The Experimental Population Area, recovery zones, and the Fort Apache Indian Reservation were manually digitized from a USFWS map image using the Editor toolbar in ArcGIS. All data were imported into Arc 10 and projected in NAD 1927, UTM Zone 12N.

Wolf Habitat Modeling

Two methods were tested for modeling wolf habitat: a rule-based deductive approach and an inductive presence-only method using the MaxEnt distribution-modeling program. The MaxEnt software requires the use of species locality points, which were approximated by taking random sample points within the current Mexican wolf pack home ranges. Due to certain inaccuracies in the MaxEnt model results (see Appendix 1), a deductive approach was chosen.

Experimental Study Area:

The rule-based deductive model was created with environmental variables chosen based on literature review, consultation with a Mexican wolf biologist, and information gleaned from specific MaxEnt outputs (Appendix 1). Slope and percent canopy did not appear to have predictive power in any of the MaxEnt iterations completed, and were therefore not included. The deductive model incorporated land use/land cover type (MRLC NLCD, Xian et al. 2009), human density (CIESIN), and elevation (USGS NED). NLCD land cover classes deemed suitable included evergreen forest, deciduous forest, mixed forest, grassland/herbaceous, woody wetlands, and emergent herbaceous wetlands. All areas with a human density lower than 8 people per km^2 were selected for inclusion as well. Elevation was set above 1,370 meters, as the vast majority of historical Mexican wolf presence has occurred above this limit (AZGFD).

Once the binary, deductive Mexican wolf distribution model had been created, the percent of pixels considered habitat within a 480 km^2 window was calculated. This window size was chosen because it is the average size of a Mexican wolf pack home range. A threshold of 0.8 was set on the resulting map layer, meaning that all 480-km^2-areas comprised of at least 80% "suitable habitat" pixels were considered habitat. This cutoff was chosen based on examination of the pack data. For each pack recorded in the area between 1998 and 2009, only about 77% of its habitat would be deemed "suitable" as far as forest cover. Therefore, a threshold of 80% habitat area was determined to be reasonable. This threshold effectively divided habitat within the study area into patches. All patches smaller than 230 km^2 were removed because the smallest home range of any persistent pack observed in the current BRWRA is 233.76 km^2. Finally, all patches within 5 km of each other were grouped together as a functional unit. This is because wolves typically move along a hunting runway of approximately 112 km every 9 days (AZGFD), so 5 km would be an easy distance to travel. Patches within this distance were considered functionally connected "subnetworks" for the purposes of this study (Figure 2).

Expanded Study Area:

Several adjustments were made to these methods once the study area was expanded to include the four-state region of Arizona, Colorado, New Mexico, and

Utah. Firstly, land cover types selected were limited to evergreen forest, deciduous forest, mixed forest, and woody wetland. Elevation and human density requirements remained the same, but a rule necessitating a distance of at least 200 m from major roads was added (Figure 5). Habitat patches were developed directly from this habitat model by using the Region Group tool in ArcGIS 10 and then removing any patch smaller than 480 km^2 (the average size of existing wolf pack home ranges in the BRWRA). See Figures 6 and 7.

Threat Analysis

Experimental Study Area:

Since the two major threats to wolf survival (illegal shooting and vehicle collision) were not incorporated into the distribution model, threat analyses were performed in order to get an idea of how secure each habitat patch was from human influences such as roads and ranches. Most studies use road density rather than distance from roads as an indicator of wolf presence (Larsen and Ripple 2006, Fuller et al 1992, Mladenoff et al 1995, Mech 1988, Oakleaf et al. 2006, Theil 1985). However, New Mexico and Arizona are significantly less developed than many states, so distance from roads was considered a more realistic measurement in this situation. A study performed by Whittington et al. (2004) suggests that wolves strongly select for distances greater than 200 m from roads. Threat categories based on distance from roads in order of severity were assigned as follows: 0–200 m, 200 m–1 km, 1 km and above. Threat categories based on distance from ranches in order of severity were assigned as follows: 0–1 km, 1–2 km, 2–3 km, 3–4 km, > 4km. Ranch distance and road distance threats were then combined into one layer with a

Weighted Overlay tool, using a scale from 1 to 5 and a percent influence ratio of 60:40 (for ranches and roads, respectively). In this stage of the project, this information was only used to calculate threat statistics per subnetwork in order to come to conclusions regarding the safety of each habitat area. Table 3 summarizes this information.

Table 3: Subnetworks Ranked by Exposure to Threat

Experimental Study Area: Threat Value Statistics			
Subnetwork	**Mean Threat Value**	**Minimum Value**	**Maximum Value**
2	1.41	1	5
1	1.36	1	4
5	1.28	1	5
3	1.16	1	5
4	1.08	1	3

Expanded Study Area:

As the scope of the study expanded, adjustments were made to the threat analysis described above in order to increase accuracy and applicability to the project. Firstly, variations in threat between major and minor roads were taken into account. Major roads were considered to be highways and interstates. Municipal roads, county roads, and state routes were considered minor. Each of these threat categories were divided into four threat classes based on distance (see Table 4 for details). These threat categories were then combined with a Weighted Overlay tool, using a scale of 0-200 and set to equal influence. Differences in assigned threat values are representative of the impact each category tends to have on wolf populations.

Table 4: Assigned Threat Values, Expanded Study Area Threat Analysis

Four-State Study Area: Threat Analysis	
Threat Category and Class	**Threat Value**
Distance from Ranch	
0-1 km	0
1-2 km	50
2-4 km	150
>4 km	200
Distance from Major Road	
0-200 m	0
200-500 m	50
500-1000 m	125
>1000 m	150
Distance from Minor Road	
0-100 m	0
100-200 m	25
200-500 m	50
>500 m	75

Corridor Delineation

Experimental Study Area:

Once this had been completed, it was necessary to analyze connectivity between habitat patches. A cost surface was created by inversing the habitat model developed earlier. This was used to calculate the number of "cost units", or the units of energy/resources, it would take for an individual to get from one patch to another based on distance and harshness of the landscape. These "cost distances" were calculated to and from each isolated area of habitat, using the patch containing the BRWRA as the source patch, producing a number of corridors throughout the study area (Figure 3).

Expanded Study Area:

The cost surface was further developed for the larger study area. Land cover types from the NLCD (90 m, MRLC NLCD, Xian et al. 2009) were ranked and assigned cost values based on information from the literature on a scale from 0 to 100. These values were combined with the values assigned in the threat analysis to construct the final cost surface (Table 5).

Table 5: Values Used for Cost Surface Creation

Final Cost Surface Values: Combined Land Cover and Weighted Threats			
Land Cover Type	**Cost Value**	**Threat Class**	**Cost Value**
Open Water	100	**Distance from ranches**	
Perennial ice/snow	55	0-1 km	1
Developed,open	85	1000-2000 km	50
Developed, low	90	2000-4000 km	150
Developed, medium	95	> 4000 km	200
Developed, high	100	**Distance from minor roads ***	
Barren land	60	0-100 m	1
Deciduous forest	1	100-200 m	25
Evergreen forest	1	200-500 m	50
Mixed forest	1	> 500 m	75
Shrub/scrub	30	**Distance from major roads ****	
Grassland/herbaceous	40	0-200 m	1
Pasture/hay	80	200-500 m	50
Cultivated crop	75	500-1000 m	125
Woody wetland	10	> 1000 m	150
Emergent herbaceous wetland	45		

*For the purposes of this study, municipal, county, and state roads constitute minor roads.
**For the purposes of this study, U.S. highways and interstates constitute major roads.

Results:

Preliminary objectives of this study required analyzing the expanded, four-state study area, results for this aspect of the project alone will be described and discussed in the following sections.

<u>Habitat Modeling</u>

Figure 5 displays the variables used in the development of the deductive habitat model. Results for the habitat model and habitat patches created can be viewed in Figure 6 and 7, respectively. There is approximately 181,584 km^2 of suitable Mexican wolf habitat extending throughout the states of Arizona, Colorado, New Mexico, and Utah. These are divided into 59 separate habitat patches with areas of at least 480 km^2. The largest of these is located in southwestern Colorado and is 23,202 km^2 in size (Patch 1 in Figure 8).

Connectivity

The cost surface used to perform corridor analyses can be viewed in Figure 9. Potential corridors exist between all of the major areas of Mexican wolf habitat identified throughout the Southwest. It appears that dispersal to large areas of habitat in Utah and Colorado is very possible through linkages stretching to the Northwest and Northeast of the BRWRA (Figure 10). However, some of these connections are less than 1 km wide in certain areas, most notably in an area connecting the BRWRA to Patch 1, mentioned (Figure 11).

Discussion and Conclusions:

Significant Findings

There is approximately 181,584 km^2 of suitable wolf habitat throughout the region of study (Arizona, Colorado, New Mexico, and Utah). This potential habitat is fragmented into 59 "patches" of habitat, with at least 480 km^2 of area. The largest of these (labeled as Patch 1 in Figure 8) is located in southwestern Colorado and comprises 23,202 km^2 of land. For comparison, the BRWRA has a total area of 17,740 km^2. There are currently 9 wolf packs that have been persistent in the BRWRA for over three years. Given these numbers, it is reasonable to assume that Patch 1 may be capable of supporting approximately 12 wolf packs. With an average of 4-8 wolves per pack, this would mean that anywhere from 48 to 96 individuals could survive within the bounds of this particular area.

If this area is extended to include Patches 2 and 4 (Figure 8) as well, the total area is 46,848 km^2, which would increase the estimated number of possible wolves to 96-192. It is important to note that this is an extremely conservative estimate, given that the area of land available to Mexican wolves in the BRWRA is not yet being fully utilized due to high wolf mortality. It is therefore likely that both patches could support many more individuals than these numbers imply.

As can be seen in Figures 9 and 10, there are a great deal of potential corridors connecting habitat patches identified in this study. An interesting result of this analysis is the fact that there are unbroken linkages running from the source patch (BRWRA) all the way up through central (and even northern) Colorado and Utah. This is very promising for the purposes of natural Mexican wolf dispersal.

However, while there is a substantial amount of favorable wolf habitat and potential dispersal paths, it is necessary to point out the tenuous nature of one critical pathway. Figure 11 displays a corridor that would be essential for a dispersal path from the BRWRA to Patch 1 in southwestern Colorado. This corridor is about 42 km long and less than 1km wide in some areas. This threatened corridor carefully follows the scattered line of forest that remains in its proximity. Conversion of forested land cover to pasture, hay, and cropland exacerbates the difficulties that Mexican wolves already face in crossing harsh terrains (shrub, desert, grassland etc.) of the Southwest.

The quality of source and destination patches is almost as important as the pathway between them (Harrison and Chapin 1998, Harrison and Bruna 1999). Functional connectivity does not exist in a landscape unless individuals not only disperse from a source patch, but also successfully establish themselves in the destination patch (Carroll 2006). There are often significant obstacles to dispersal from a source patch, such as human development and geological barriers. If the destination patch is isolated or of insufficient size in addition to these difficulties, then even a successful journey will likely end up in failure (such as death, hybridization etc.). These are factors that must be considered in management decisions regarding natural dispersal versus reintroduction projects. Given these factors, Patch 1 and its surrounding areas are a promising site for future reintroduction projects. As mentioned above, this area covers 46,848 km^2. Of this, 14,261 (30.44%) km^2 is already protected as designated Wilderness Area, National Forest, or State Forest etc., increasing the likelihood that it will remain relatively suitable wolf habitat in the future.

Limitations

Many assumptions were used in the process of this analysis. Firstly, all distance and cost thresholds were subjective by nature; they were best estimates based on information from the literature. There were also several assumptions made in the creation of the deductive habitat model. For instance, when extracting certain habitat types from the NLCD, land cover such as grass and shrubland was left out. Although wolves do not prefer these habitats, given their incredibly adaptable nature, they may be able to survive in such terrain on a temporary basis. On the other hand, while forest cover is ideal, it becomes less valuable when there is human development or ranchland nearby. Also, although an extensive literature review was performed in order to determine which factors are most significant in wolf distribution, this does not mean that the factors chosen in this study produced the most accurate results. Additionally, creating rigid lines in a habitat model (such as separating pixels into binary layers of habitat versus non-habitat) is unavoidable, but also unnatural and uncompromising. In general, any modeling technique will predict false absences and false presences because a species will not necessarily inhabit every location where certain factors are conducive to their survival, and they sometimes will survive in areas that do not seem accommodating. These assumptions were necessary in order for analyses to progress, but may have had an effect on the accuracy of the end product.

Aside from the assumptions mentioned above, this project had several limitations. Firstly, this study did not include analyses regarding the likely ability of habitat patches to support viable wolf populations. The methods utilized incorporated patch size and basic environmental requirements, but there are many other factors that can influence population-level processes across a landscape. Secondly, there are a great number of innovative approaches to modeling connectivity (e.g. Spatially Explicit Population Models, CircuitScape, etc.). These methods were outside the scope of this project, but would be interesting to explore and compare in the region studied here.

Future Work

Further study should be considered in several areas pertaining to this study. Firstly, the discussion between natural recolonization and reintroduction should be analyzed. Exploration with a Spatially Explicit Population Model (SEPM) following the methodologies of Carroll et al. (2002, 2004) and Carroll (2003) would be a reasonable way to answer this type of question. SEPMs can evaluate dynamic, landscape-scale demographic changes in a cost-effective manner. This type of tool can also aid in the process of patch prioritization by predicting the population viability of a patch in the future.

Another important component of future work will be further and more in-depth connectivity analyses. Using graph theory methods, for example, may identify more pathways for dispersal and further aid in the prioritization of habitat for conservation. Furthermore, if natural recolonization is to remain an option in the future, close attention will have to be paid to existing corridors among the patches identified in this study. Given the fact that certain critical linkages are highly threatened, this should be a high priority for conservation action.

Conclusions and Recommendations

Findings reveal that there is sufficient habitat available to support the recovery of the Mexican wolf. Aside from further studies regarding Mexican wolf dispersal potential and reintroduction feasibility, the most crucial recommendation for interested parties is to engage in intensive, long-term educational outreach. The greatest threat to wolf survival is anthropogenic resistance. Wolves have long been persecuted and feared in this part of the country, and it is somewhat understandable given the societal reliance on livestock ranching operations in the Southwest. Luckily, the Mexican wolf has facts on its side. Although wolves have most definitely been known to prey on livestock, they are responsible for less than 1% of livestock losses (J. Oakleaf, personal communication). If recovery of the Mexican wolf is to succeed, a combination of education, appropriate husbandry practices, and available compensation/insurance programs will be needed. With local support, Mexican wolf conservation activities will likely be able to meet appropriate recovery goals and re-establish this species throughout its historic range.

Appendix 1:

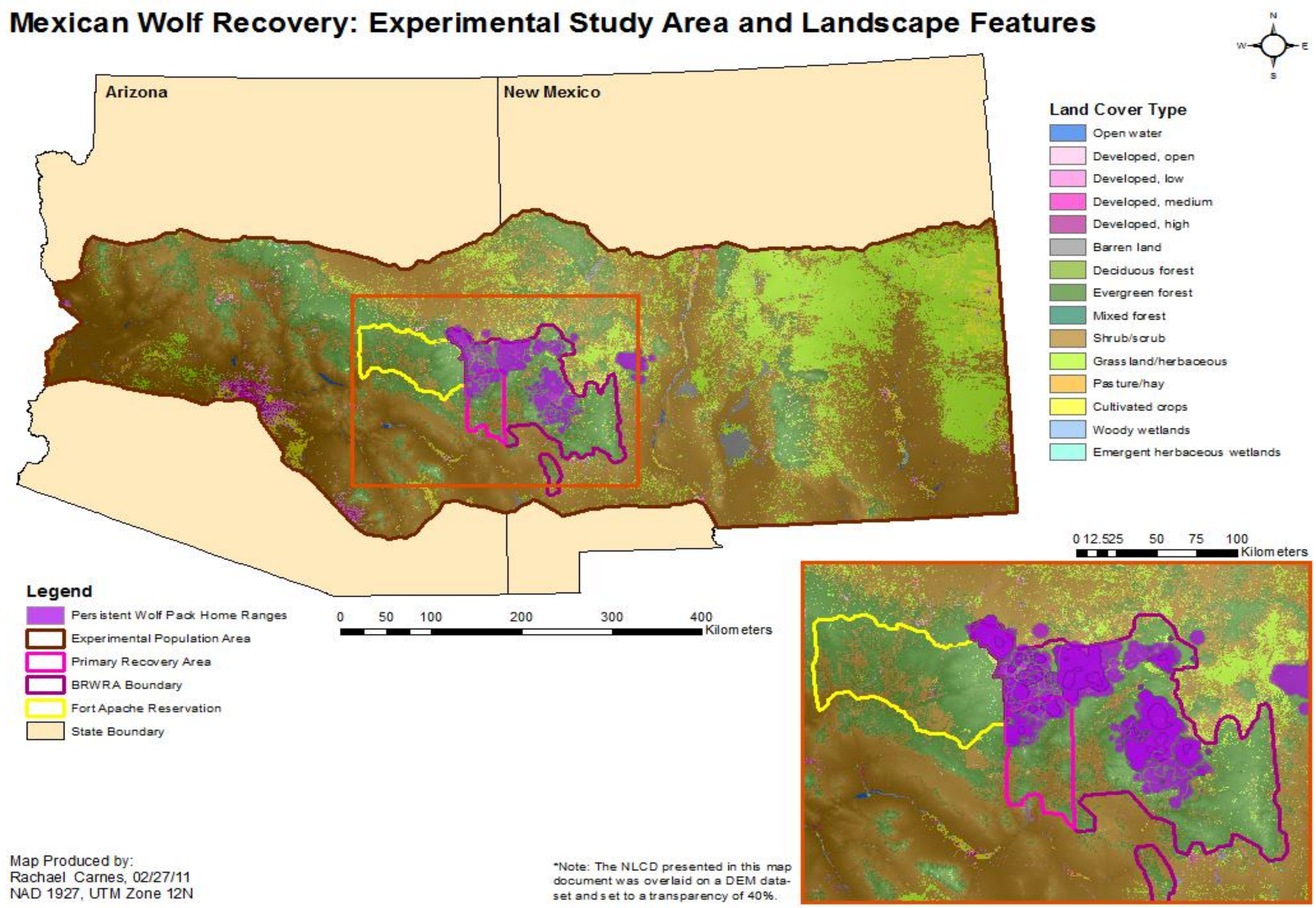


Figure 1

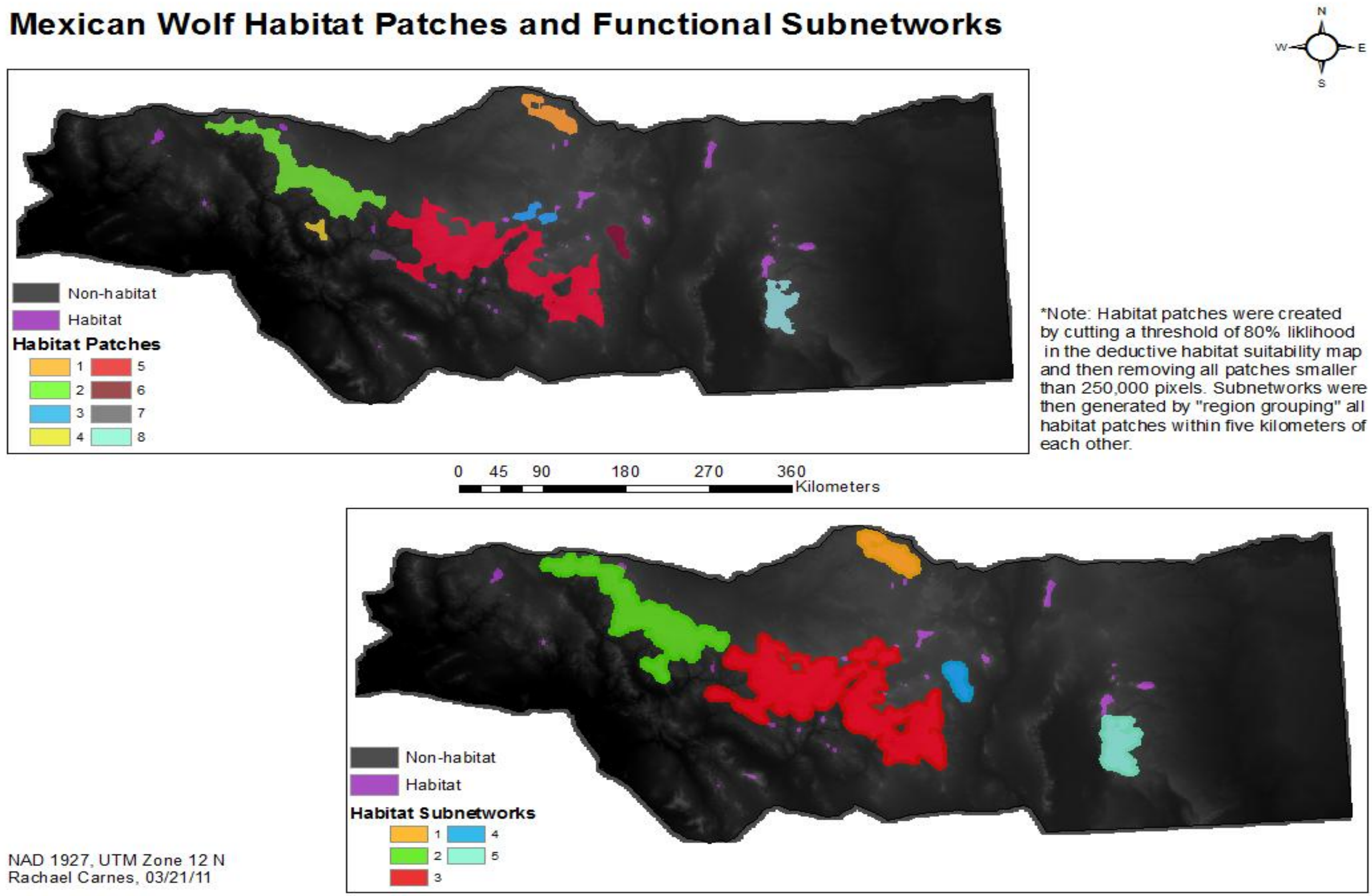

Mexican Wolf Habitat Patches and Functional Subnetworks
N
W
E
S
Non-habitat
Habitat
Habitat Patches
1
2
3
4
5
6
7
8
*Note: Habitat patches were created by cutting a threshold of 80% liklihood in the deductive habitat suitability map and then removing all patches smaller than 250,000 pixels. Subnetworks were then generated by "region grouping" all habitat patches within five kilometers of each other.
0 45 90 180 270 360
Kilometers
Non-habitat
Habitat
Habitat Subnetworks
1
2
3
4
5
NAD 1927, UTM Zone 12 N
Rachael Carnes, 03/21/11

Figure 2

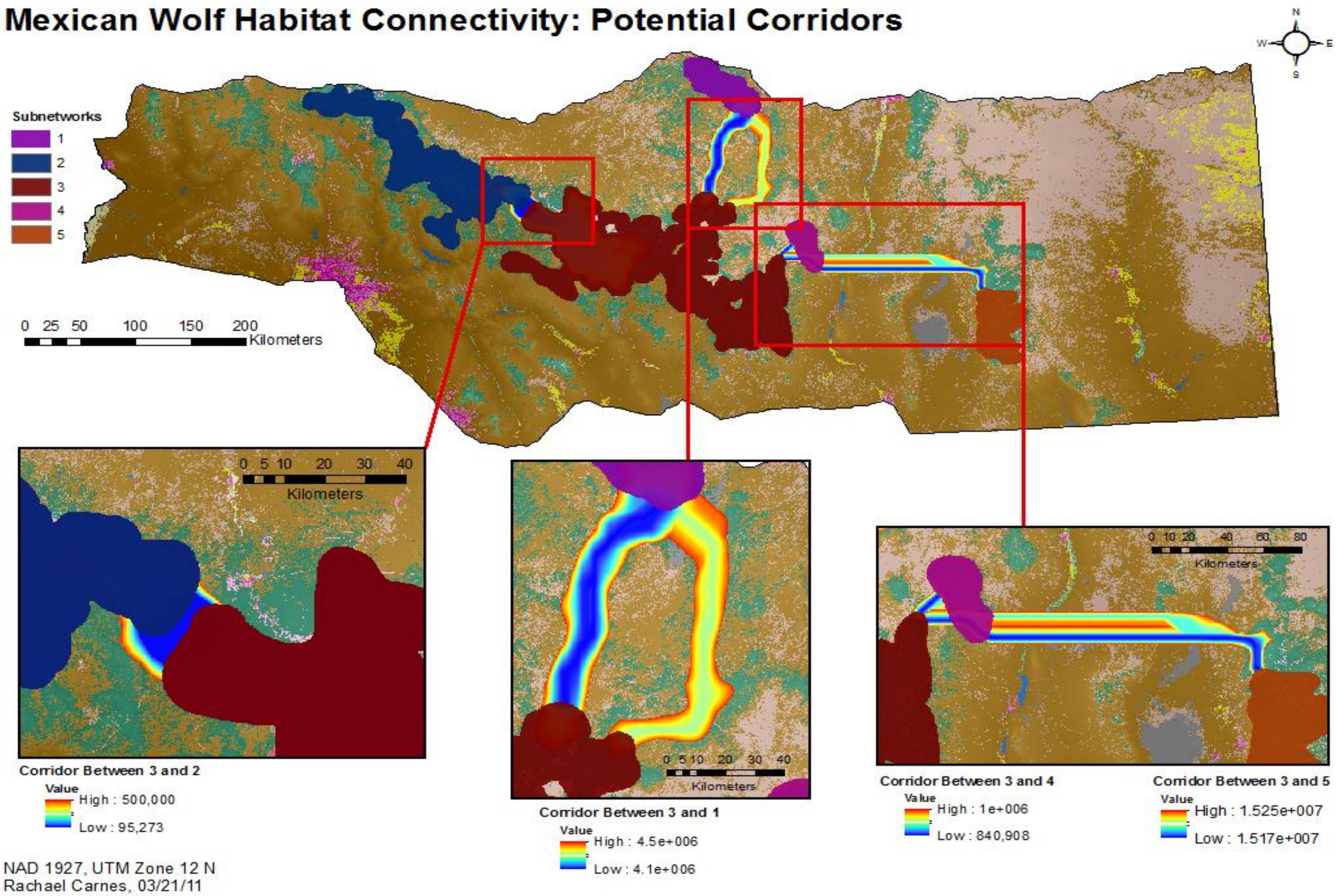

Mexican Wolf Habitat Connectivity: Potential Corridors
N
W
E
S
Subnetworks
1
2
3
4
5
0 25 50 100 150 200
Kilometers
0 5 10 20 30 40
Kilometers
Corridor Between 3 and 2
Value
High : 500,000
Low : 95,273
0 5 10 20 30 40
Kilometers
Corridor Between 3 and 1
Value
High : 4.5e+006
Low : 4.1e+006
0 10 20 40 60 80
Kilometers
Corridor Between 3 and 4
Value
High : 1e+006
Low : 840,908
Corridor Between 3 and 5
Value
High : 1.525e+007
Low : 1.517e+007
NAD 1927, UTM Zone 12 N
Rachael Carnes, 03/21/11

Figure 3

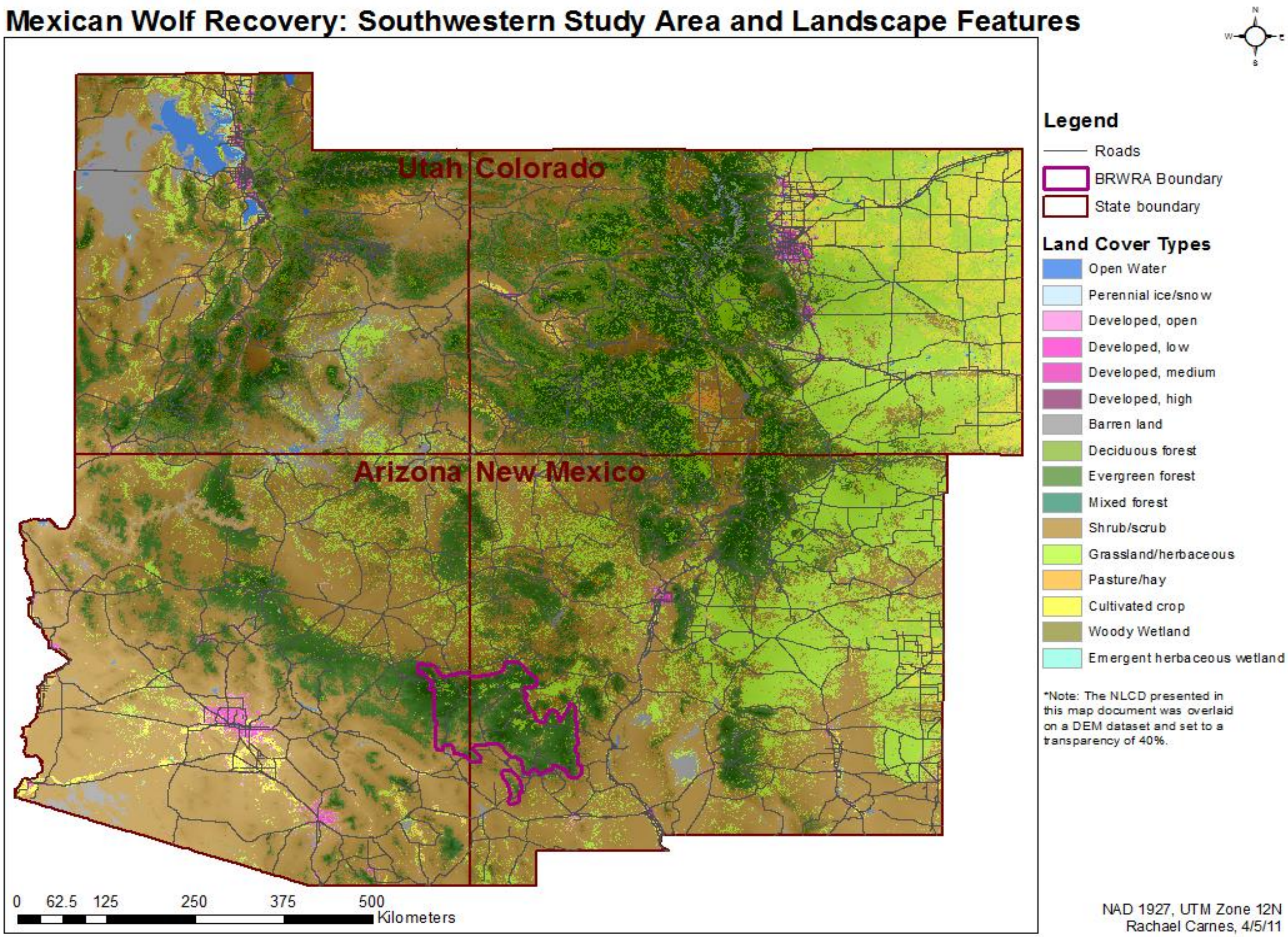

Mexican Wolf Recovery: Southwestern Study Area and Landscape Features
Utah
Colorado
Arizona
New Mexico
0
62.5
125
250
375
500
Kilometers
Legend
Roads
BRWRA Boundary
State boundary
Land Cover Types
Open Water
Perennial ice/snow
Developed, open
Developed, low
Developed, medium
Developed, high
Barren land
Deciduous forest
Evergreen forest
Mixed forest
Shrub/scrub
Grassland/herbaceous
Pasture/hay
Cultivated crop
Woody Wetland
Emergent herbaceous wetland
*Note: The NLCD presented in this map document was overlaid on a DEM dataset and set to a transparency of 40%.
NAD 1927, UTM Zone 12N
Rachael Carnes, 4/5/11

Figure 4

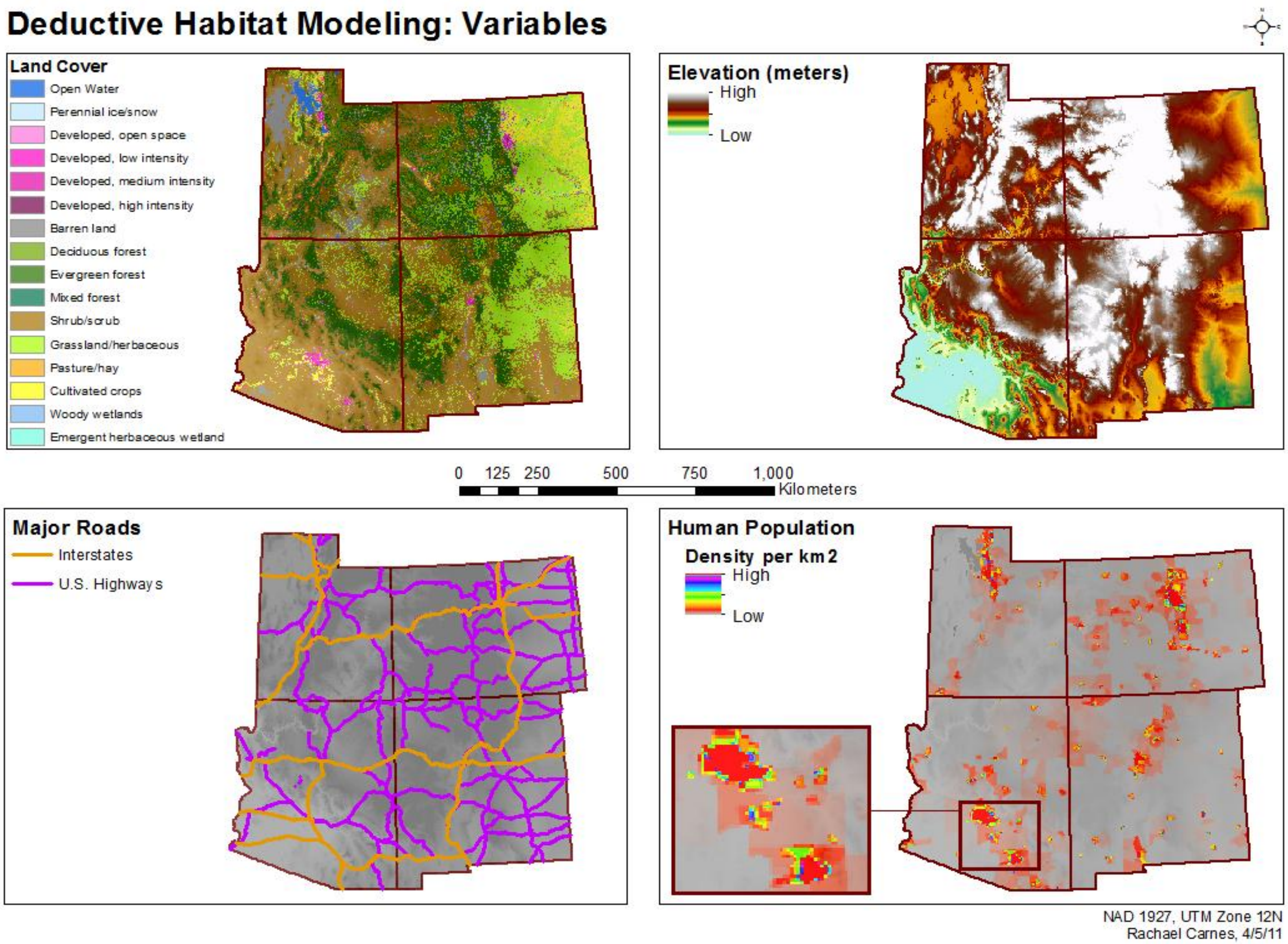

Deductive Habitat Modeling: Variables
Land Cover
Open Water
Perennial ice/snow
Developed, open space
Developed, low intensity
Developed, medium intensity
Developed, high intensity
Barren land
Deciduous forest
Evergreen forest
Mixed forest
Shrub/scrub
Grassland/herbaceous
Pasture/hay
Cultivated crops
Woody wetlands
Emergent herbaceous wetland
Elevation (meters)
High
Low
0 125 250 500 750 1,000
Kilometers
Major Roads
Interstates
U.S. Highways
Human Population
Density per km2
High
Low
NAD 1927, UTM Zone 12N
Rachael Carnes, 4/5/11

Figure 5

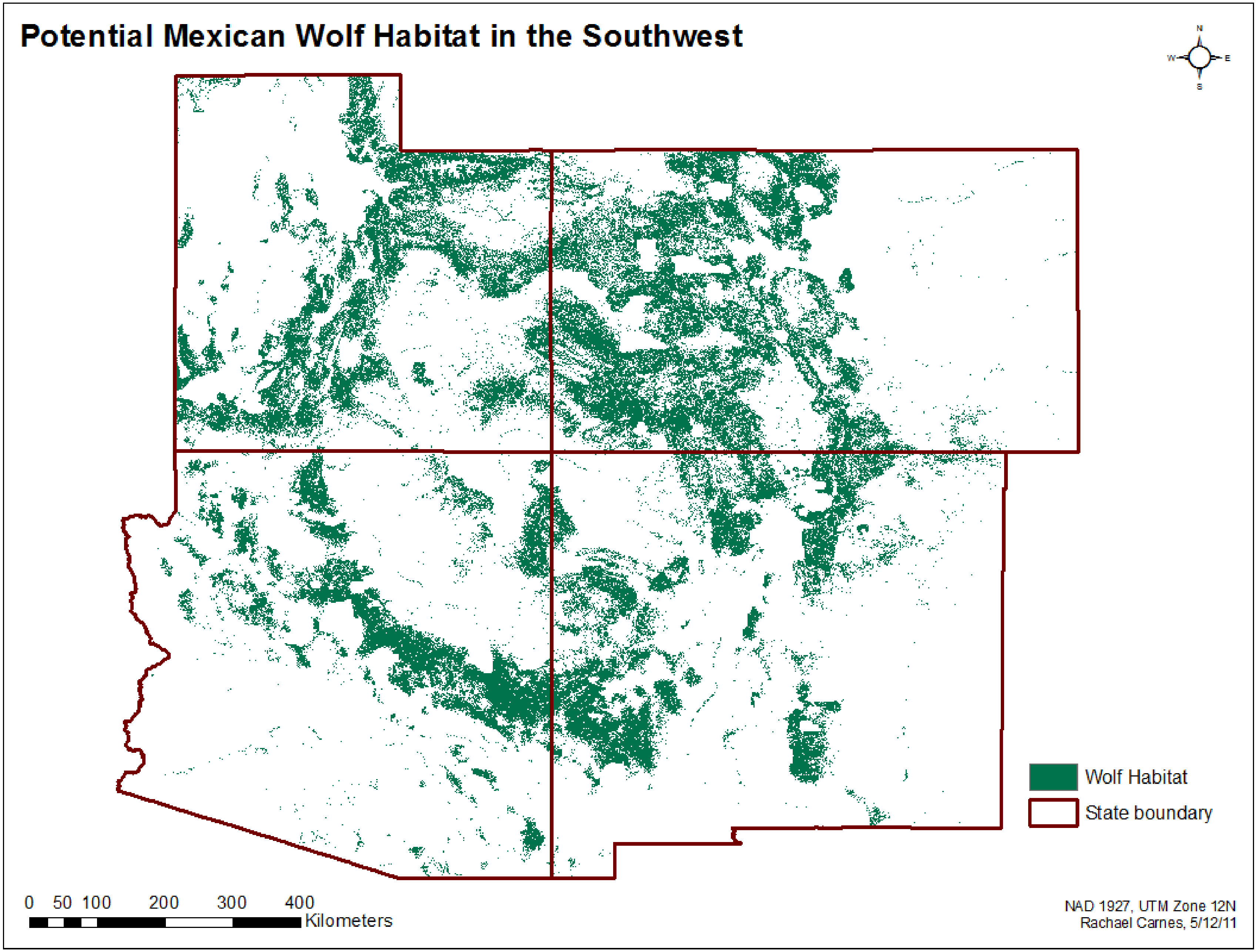
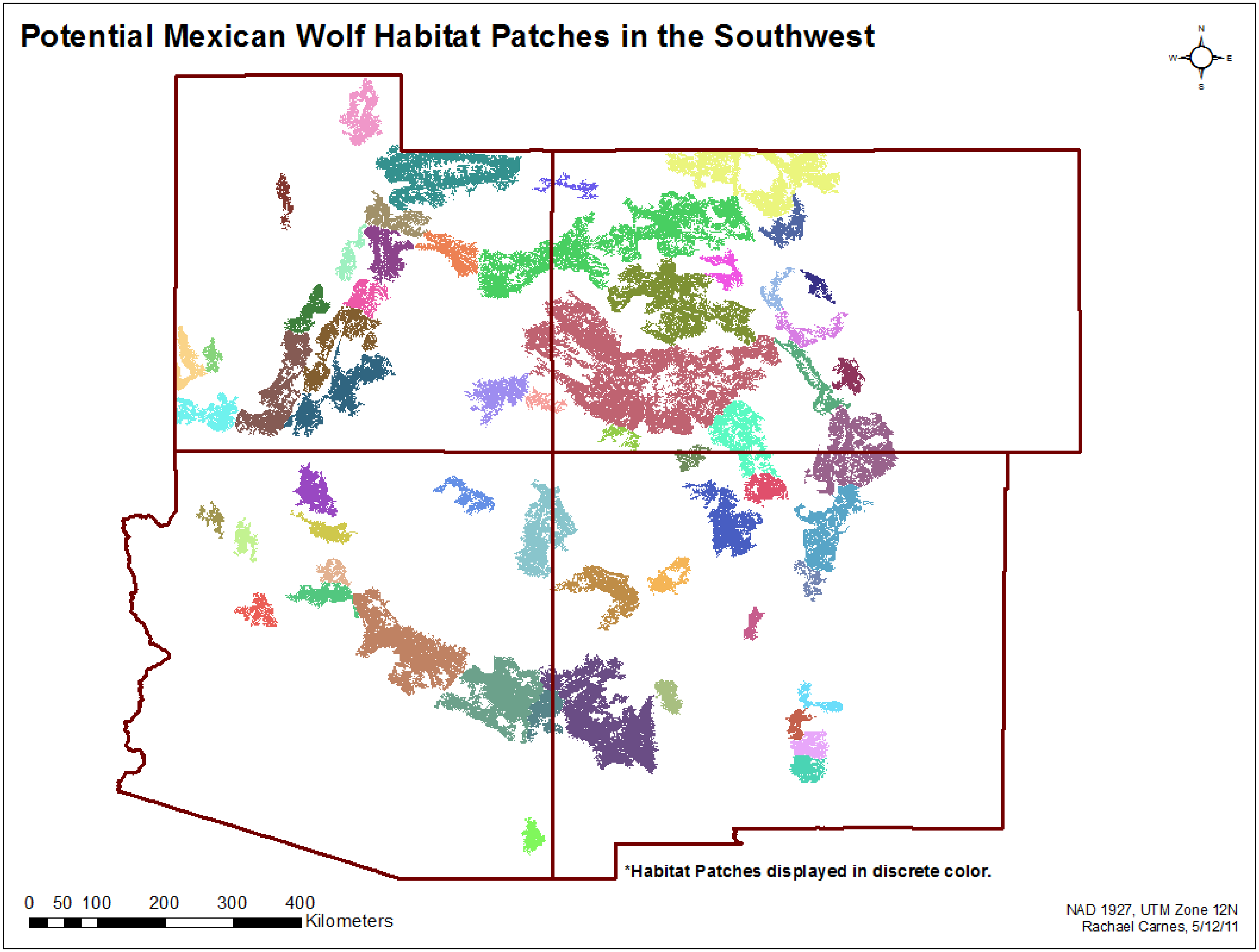
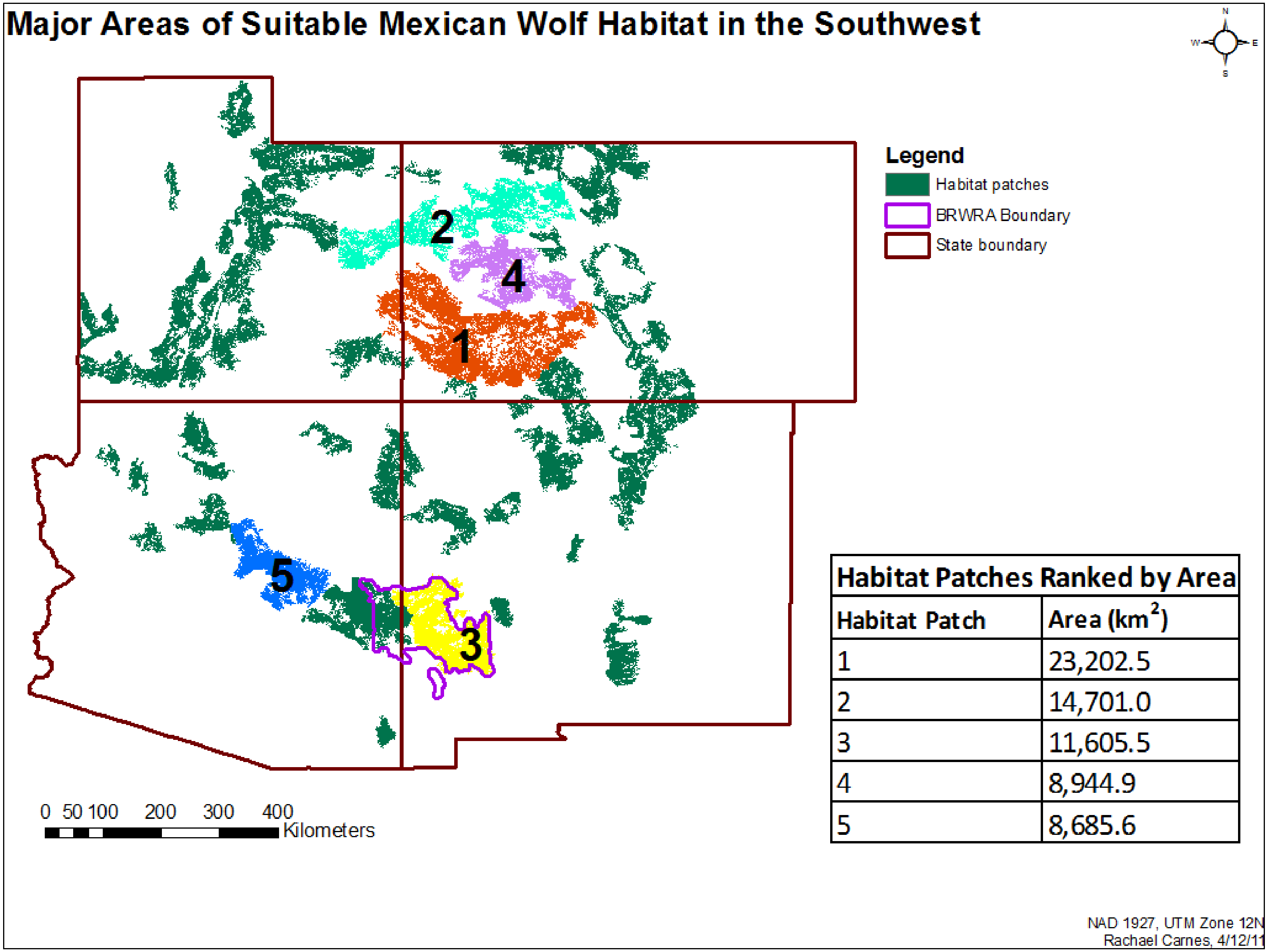

Potential Mexican Wolf Habitat in the Southwest
N
W
E
S
Wolf Habitat
State boundary
0 50 100 200 300 400
Kilometers
NAD 1927, UTM Zone 12N
Rachael Carnes, 5/12/11

Figure 6



Potential Mexican Wolf Habitat Patches in the Southwest
*Habitat Patches displayed in discrete color.
0 50 100 200 300 400
Kilometers
NAD 1927, UTM Zone 12N
Rachael Carnes, 5/12/11

Figure 7



Habitat Patches Ranked by Area	
Habitat Patch	Area (km^2)
1	23,202.5
2	14,701.0
3	11,605.5
4	8,944.9
5	8,685.6

Figure 8

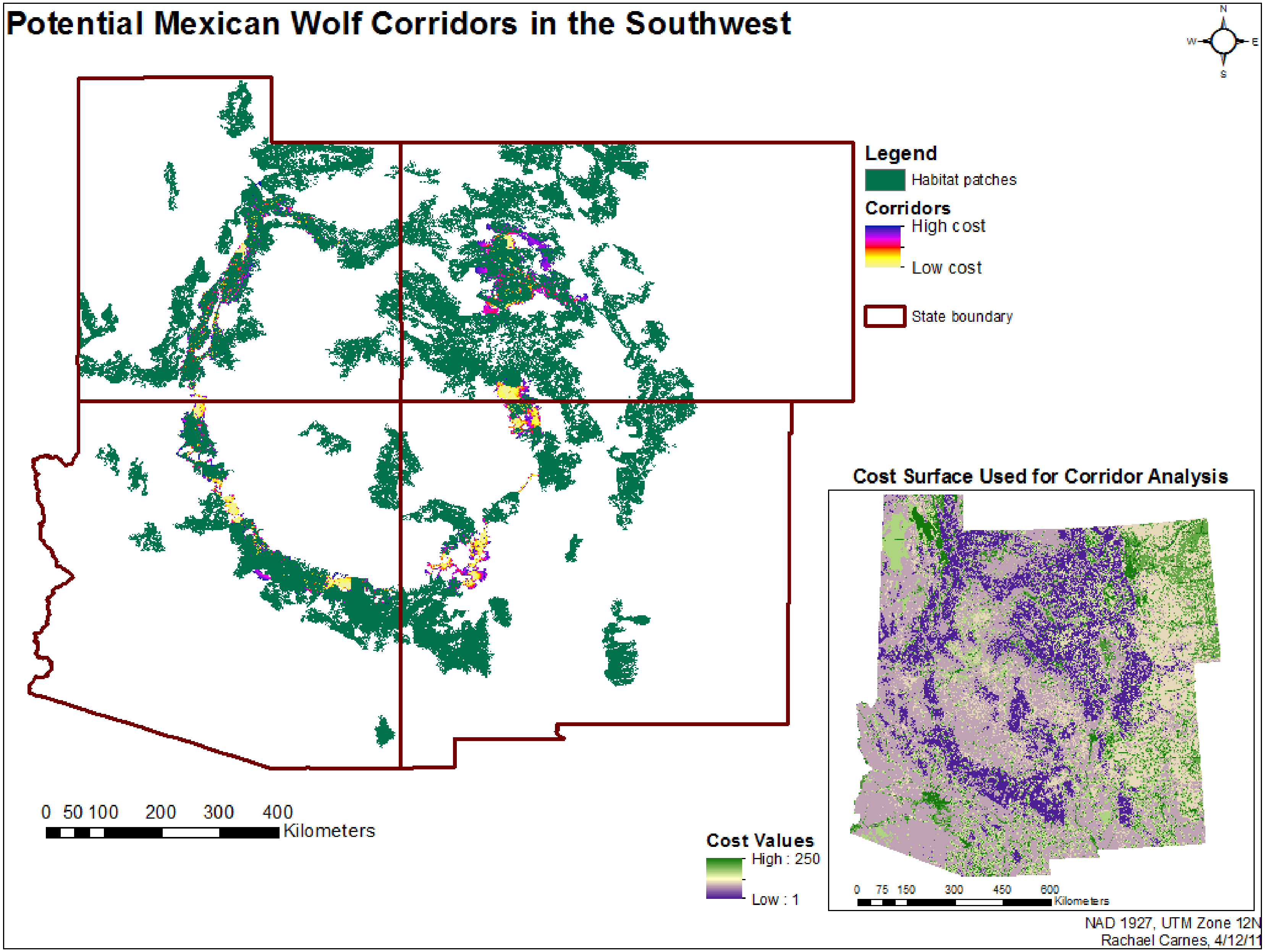

Potential Mexican Wolf Corridors in the Southwest
N
W
E
S
Legend
Habitat patches
Corridors
High cost
Low cost
State boundary
Cost Surface Used for Corridor Analysis
0 50 100 200 300 400
Kilometers
Cost Values
High : 250
Low : 1
0 75 150 300 450 600
Kilometers
NAD 1927, UTM Zone 12N
Rachael Carnes, 4/12/11

Figure 9

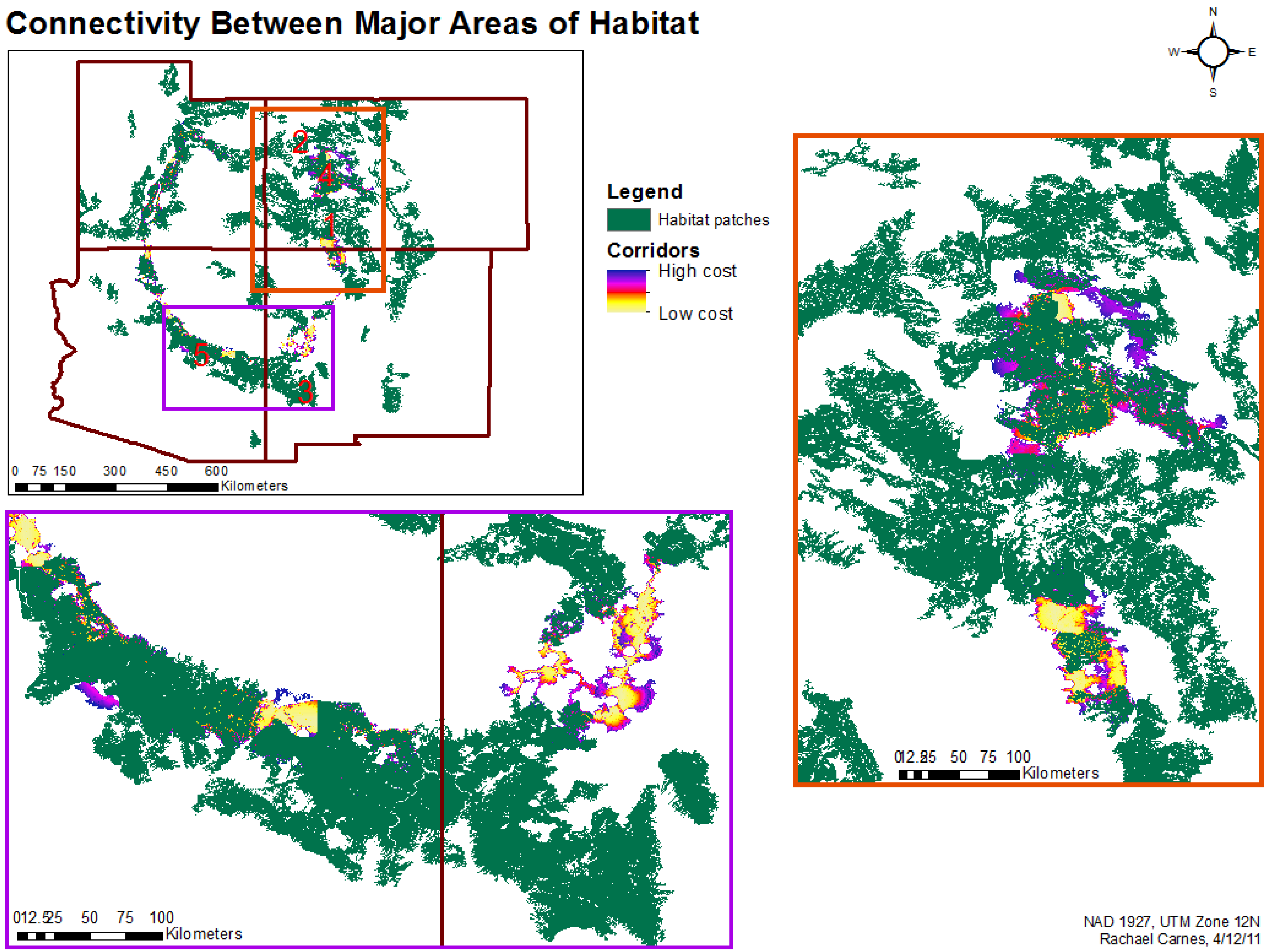

Connectivity Between Major Areas of Habitat
N
W
E
S
2
4
1
5
3
0 75 150 300 450 600
Kilometers
Legend
Habitat patches
Corridors
High cost
Low cost
012.25 50 75 100
Kilometers
012.525 50 75 100
Kilometers
NAD 1927, UTM Zone 12N
Rachael Carnes, 4/12/11

Figure 10

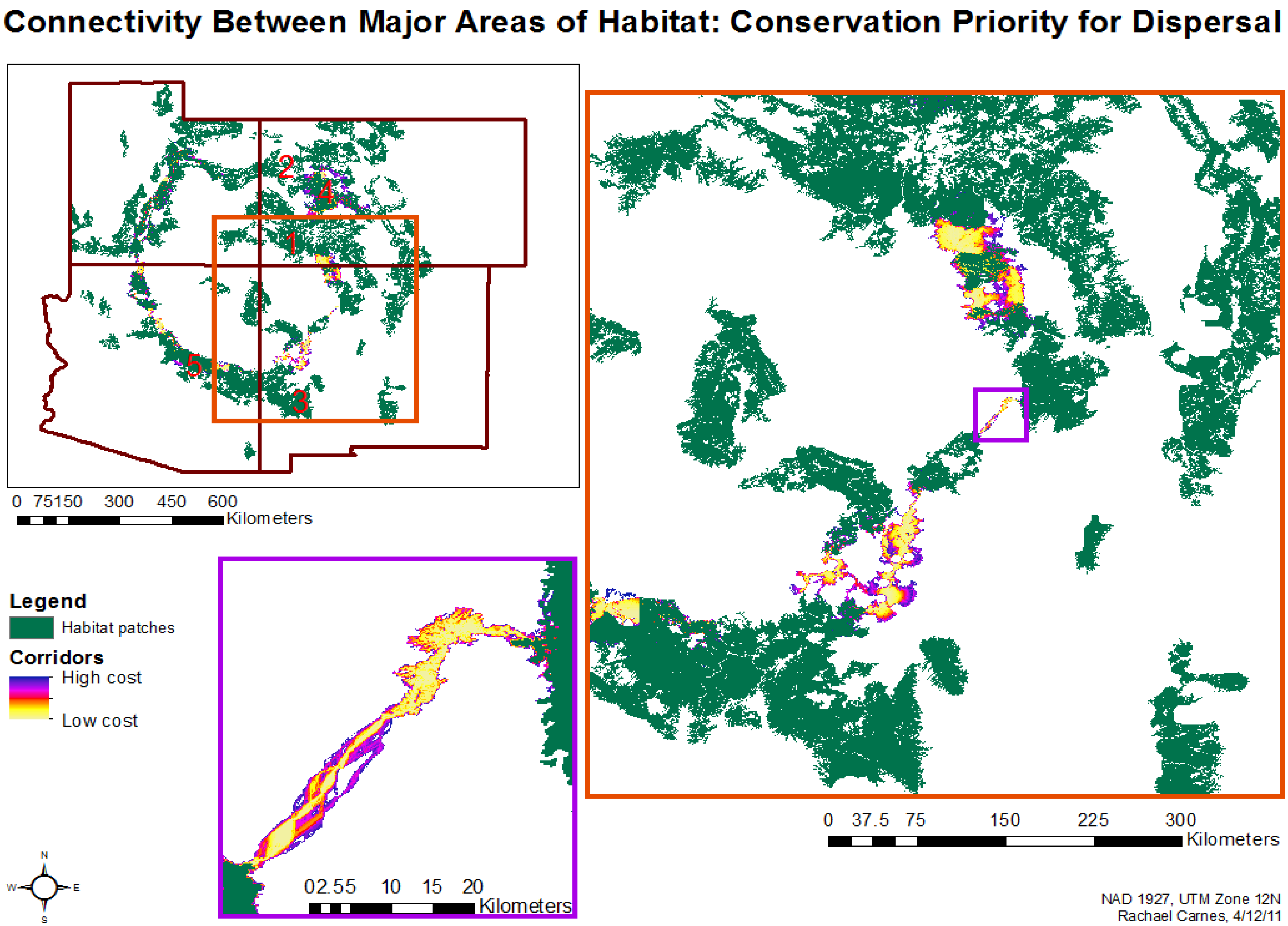

Connectivity Between Major Areas of Habitat: Conservation Priority for Dispersal
2
4
1
5
3
0 75150 300 450 600
Kilometers
Legend
Habitat patches
Corridors
High cost
Low cost
02.55 10 15 20
Kilometers
0 37.5 75 150 225 300
Kilometers
NAD 1927, UTM Zone 12N
Rachael Carnes, 4/12/11
N
W
E
S

Figure 11

Appendix 2:

Wolf habitat was predicted with two different approaches, using the species distribution algorithm and wolf pack ranges, and a rule-based deductive model. Species distribution was modeled with MaxEnt software, which offers a presence-only species distribution model, requiring the use of species locality points and environmental variables. Locality points were approximated by taking a random sample of points within the existing Mexican wolf pack home ranges (95% kernel). The program processes were completed iteratively with varying combinations of input variables. These environmental variables included slope, elevation, land use/land cover (30 m, MRLC NLCD, Xian et al. 2009), GAP vegetation (30m USGS NBII), distance from roads, human density, and percent canopy cover (Figure 12). Slope and elevation grids were developed from a DEM. Euclidean distance from roads throughout the study area were calculated. Wolf presence points were generated randomly within each of the 18 wolf pack polygons; 50 random points generated in each polygon creating a total of 900 points.

A binary raster of habitat versus non-habitat was created by extracting land cover types appropriate for wolves from NLCD data. These land cover classes included: evergreen, deciduous, and mixed forest, grasslands, and woody wetlands. A focal statistics tool was then used to convert this binary layer to a continuous raster of generalized habitat by using a moving window to calculate percentages of habitat pixels across the raster layer, with values ranging from zero to one.

The strongest of the seven MaxEnt models resulted from the variables: slope, elevation, land cover suitability, distance from roads, and percent canopy. Figure 13 compares this result to an envelope model, built using elevation, land cover, and human density requirements.

MaxEnt was used to produce statistics and identify the most useful environmental variables for current wolf habitat. These variables were then used to locate areas of suitable habitat throughout the Experimental Population Area. In every combination of environmental variables, slope and percent canopy displayed very little predictive power and were not used in further habitat modeling and analyses.

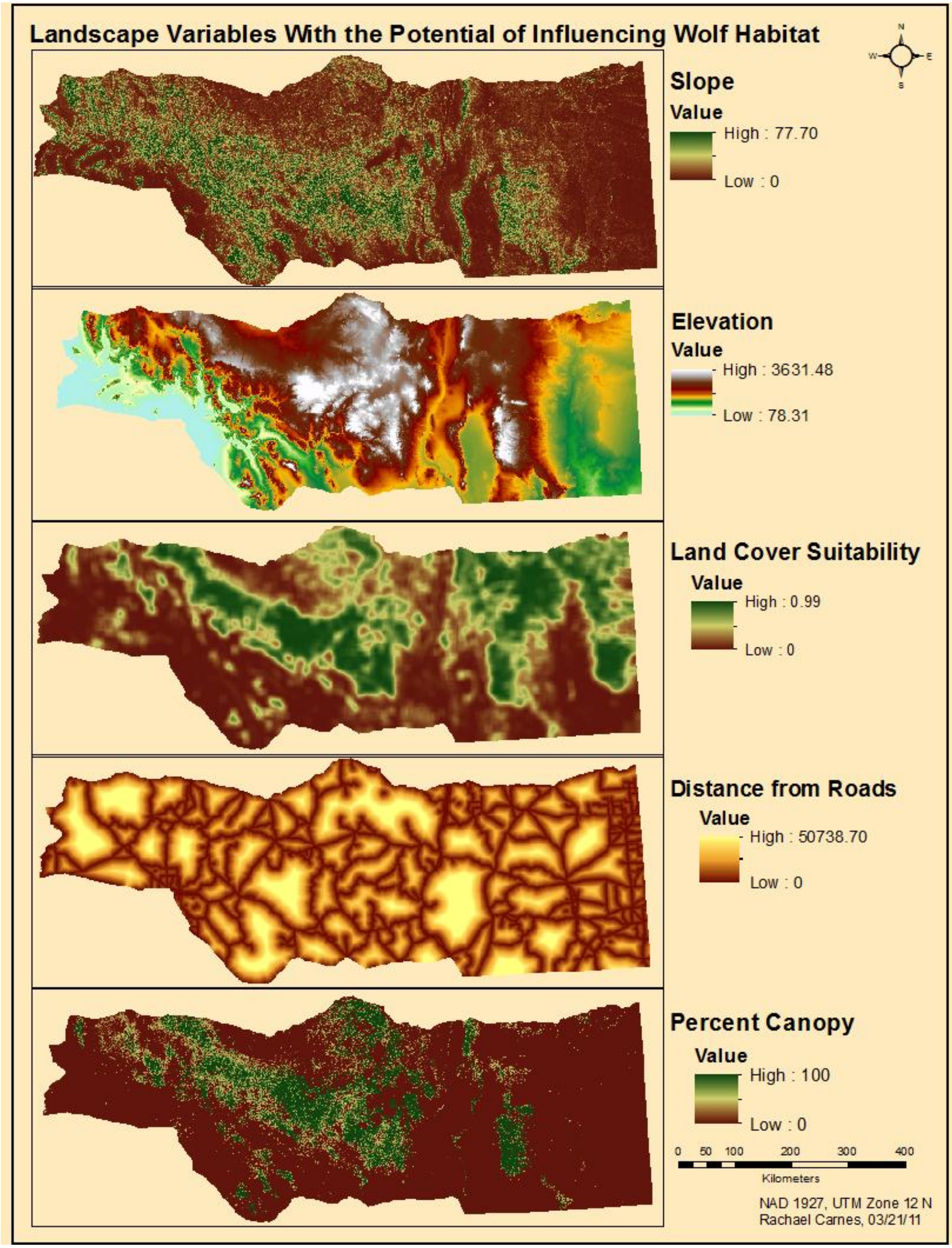

Landscape Variables With the Potential of Influencing Wolf Habitat
N
W
E
S
Slope
Value
High : 77.70
Low : 0
Elevation
Value
High : 3631.48
Low : 78.31
Land Cover Suitability
Value
High : 0.99
Low : 0
Distance from Roads
Value
High : 50738.70
Low : 0
Percent Canopy
Value
High : 100
Low : 0
0 50 100 200 300 400
Kilometers
NAD 1927, UTM Zone 12 N
Rachael Carnes, 03/21/11

Figure 13

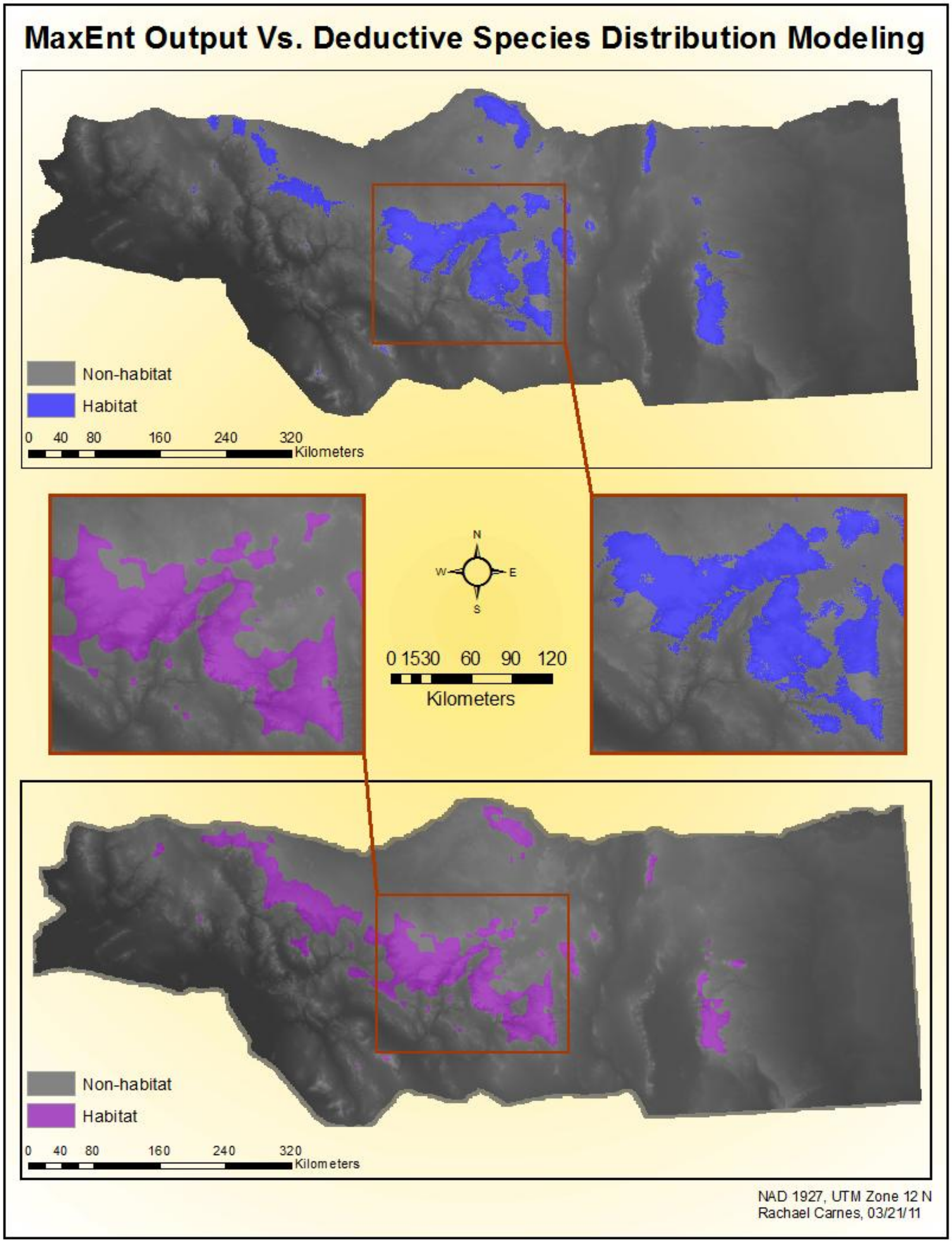

MaxEnt Output Vs. Deductive Species Distribution Modeling
Non-habitat
Habitat
0 40 80 160 240 320
Kilometers
N
W
E
S
0 1530 60 90 120
Kilometers
Non-habitat
Habitat
0 40 80 160 240 320
Kilometers
NAD 1927, UTM Zone 12 N
Rachael Carnes, 03/21/11

Figure 14

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