HABITAT CONNECTIVITY AND SUITABILITY FOR *CANIS RUFUS* RECOVERY

By

Lindsey Desmul

Master of Environmental Management Candidate

Ecosystem Science & Conservation

Dr. Dean Urban, Advisor

May 2013

Masters project in partial fulfillment of the

requirements for the Master of Environmental Management degree in

the Nicholas School of the Environment of

Duke University

Abstract

Red wolves historically lived throughout the southeastern United States. However their numbers were significantly reduced to the point of extinction in 1980. Prior to extinction, U.S. Fish and Wildlife managers were able to capture the last remaining 14 purebred wolves from the wild and put them into a captive breeding program. Once their captive population had reached a stable number, red wolves were reintroduced to the Albemarle Peninsula in North Carolina. While the reintroduction program has been successful, resulting in a growing wild population, the Albemarle Peninsula is threatened by sea level rise and there is a growing concern about habitat connectivity and the potential for wolves to move inland.

In this study, a connectivity analysis was conducted for North Carolina to determine if urban growth and sea level rise might result in decreased potential for natural movement of the wolves over the next several decades. A geospatial analysis was conducted to identify possible bottlenecks to wolf dispersal, represented by pinch points in modeled dispersal corridors. These corridors entailed creating a 'cost surface' as a map of relative resistance to wolf dispersal, with cost reflecting several variables: land cover, urban density, housing density, road density, sea level rise, and slope. Using a model of sea-level rise created by The Nature Conservancy, a rise in sea level of 0.38 meters by 2050 would cause the Alligator River National Wildlife Refuge to be highly disconnected from the mainland of North Carolina, complicating movement for a large portion of the red wolf population from their current habitat range.

Compared to current habitat connectivity, the results show that while the overall route of movement by wolves may not drastically change, several bottlenecks caused from interstate and highway density, urban sprawl, and sea level rise flooding may impair movement to some extent. These barriers can be mitigated by constructing highway under- or overpasses and planting greenway corridors to make migration safer and easier for the wolves in the future.

Dedication

This project is dedicated to my husband Ben and to my friends and family, who have supported me and kept me calm and grounded throughout this project and my education.

Acknowledgements

Thank You! to all of the contributors to this project. Without you, it would not have been possible:

Dr. Dean Urban, Professor and Division Chair at Duke University's Nicholas School of the Environment, for being my MP and Nicholas School advisor.

John Fay, Professor of GIS at Duke University's Nicholas School of the Environment, for helping with all things GIS-related.

Dr. Ron Sutherland, Wildlands Network Southeastern Region, for the expert-derived estimates for NLCD land cover resistance, funded by the South Atlantic Landscape Conservation Cooperative.

C. Belyea and J. Costanza, North Carolina State University's Biodiversity and Spatial Information Center, and A. Terando at the Department of Interior Southeast Climate Science Center, for the urban growth projection data.

Analie Barnett, Landscape Ecologist with The Nature Conservancy, for the sea level rise model and equations.

Dr. Chris DePerno, Professor at North Carolina State University, Department of Fish and Wildlife, for help with the coyote data and analysis.

Colleen Olfenbuttel, Wildlife Biologist with the North Carolina Wildlife Resources Commission, for the coyote data, and housing density data.

Will Waddell, Red Wolf Director at Point Defiance Zoo and Aquarium, for taking the time to give me a history lesson where it all began.

U.S. Fish and Wildlife Service - without your quick management decisions I would not be doing this project, and would never know the beauty of the red wolf.

Table of Contents

Introduction

Background

The red wolf (*Canis rufus*) is a canid species that historically encompassed the southeastern United States, ranging from eastern Texas to southern Pennsylvania (figure 1).

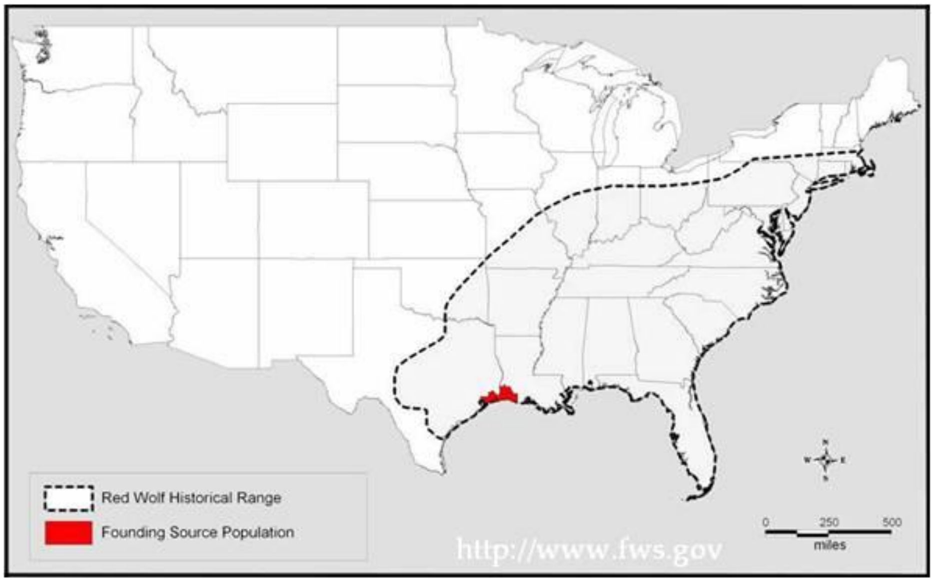

Figure 1 - Historic red wolf habitat range. The full habitat range is shaded in gray and the range in red is where the last remaining 14 wolves were taken from the wild. Courtesy of the U.S. Fish and Wildlife Service.

Smaller than the gray wolf (*Canis lupus*) and larger than the coyote (*Canis latrans*), the red wolf feeds on small rodents and rabbits as well as deer, insects, and berries (McVey, 2012). As an apex species, red wolves have no known predators aside from humans. Apex predators serve an important role in the ecosystem in which they live because they can control the population of species in the food chain below them, as well as remove unhealthy individuals. For example, wolves can help control the deer population, increasing the health of vegetation in the ecosystem by reducing herbivory (Red Wolf Coalition, 2008). This not only improves natural processes like reducing stream water temperature with increased shading, but it can provide food and habitat to other species such as beavers and birds (Smith et al., 2003; Holland, 2004). Estes et al. (2011) also claim that a decrease in apex predators could potentially increase the frequency of disease. Many apex species, including the red wolf, directly compete with carnivores such as raccoons, foxes, and opossums (Red Wolf Coalition, 2008). These smaller carnivores, or meso-carnivores, have a higher tendency to carry diseases like rabies than other animals. In fact, according to North Carolina Department of Health and Human Services data collected between 1990 and 2011, 65% of all reported rabies cases were caused from raccoon bites (Wild South, 2012). Therefore, an increase in apex predators may potentially lead to a decrease in rabies cases.

The red wolf plays a particularly important role in restoring natural ecosystem function, as compared to other predators, because it is one of the few remaining native carnivores in the southeastern United States. Lacking carnivores such as cougars and wolves, white-tailed deer have overpopulated areas ranging from Maine to Texas (Côté et al., 2004). North Carolina also experiences problems with invasive feral hogs, causing harm to crops and human health and safety (*Science Letter*, 2011), which could potentially be reduced with predation.

Species in Peril

Like many other wild canids, the red wolf was hunted to the brink of extinction until listed as federally endangered in 1973. At the time of protection, urban development had pushed the small remaining population away from suitable habitat to areas with low prey density and high coyote populations. Coyote-wolf interbreeding occurred as a result of shared habitat, and the wolves suffered from increased parasitic infection, reducing the population of pure red wolves in the wild (Fazio, 2007).

The U.S. Fish and Wildlife Service intervened in the late 1970’s and started a captive breeding program with only 14 red wolves as the breeding stock. Approximately 89.65% of the genetic variability in this founder population has been maintained with the current reintroduced population (Fazio, 2007). Reintroduction attempts took place in the 1980's in both the Smoky Mountains of Tennessee and a coastal region of North Carolina. This attempt to bring wolves back to the wild preceded the Yellowstone wolf reintroduction project, thereby laying the foundation for future wolf management efforts. Unfortunately, the introduced population in the Smoky Mountains did not succeed due to low pup survival rates caused by parasitic infection and disease (including canine parvovirus and distemper), as well as predation and starvation. The remaining wolves were removed from the Smoky Mountains in 1987, and further reintroduction sites in the region were never explored (Wheeler, 1998).

Currently, the only wild population of red wolves can be found on the Albemarle Peninsula of North Carolina. With the recovery center located in Alligator River National Wildlife Refuge and their habitat range spanning five North Carolina counties (Dare, Hyde, Tyrrell, Washington, and Beaufort), the current known population is approximately 70 wolves. This population estimate is based on the wolves that are being tracked via radio-collar or radio transmitter, however there are a number of wolves that are not being tracked. Therefore the entire wild population is predicted to be between 90 and 110 individuals (U.S. Fish and Wildlife Service 2013).

In 1988 the first litter of red wolf pups was born in the wild (U.S. Fish and Wildlife Service, 1997), and by 2002 all red wolves in the wild population had been born in the wild rather than reintroduced from captivity (U.S. Fish and Wildlife Service, 2006). Thereafter, each year in April and May new pups are born both in captivity and in the wild, further establishing the gene pool of the species (U.S. Fish and Wildlife Service, 2004). While only half of the newborns are predicted to survive, the wild births have proven the peninsula reintroduction site successful.

Cause of Death	# of Total Mortalities 2010	# of Total Mortalities 2011	# of Total Mortalities 2012	# of Total Mortalities 2013
Natural				
Health Related	4	2	1	
Intraspecific Competition	2	0	0	
Human-Related				
Management-related Actions	0	0	2	
Non-management-related Actions	0	2	0	1
Vehicle Strike	3	3	2	
Suspected or Confirmed Gunshot	6	7	8	2
Poison				
Unknown				
Lack of Biomaterial	2	5	4	
Suspected Illegal Take	0	2	1	
Pending Necropsies	0	0	1	1
Total Mortalities	**17**	**21**	**19**	**4**

Table 1 - Record of red wolf mortalities from 2010 to present. Cells left blank have not yet been recorded for the year. Courtesy of U.S. Fish and Wildlife Service.

Although the population is stabilizing, and healthy pup birth is increasing, red wolves still face many challenges. Reintroduction to the small peninsula has lead to a habitat with an over-extending carrying capacity (Fazio, 2007). The peninsula is also in danger of being partially consumed by sea level rise caused by global climate change. While many sea level rise models are estimating a 1.0 to 1.5 meter rise by the year 2100 (Bamber & Aspinall, 2013; Rahmstorf, 2011), most of the peninsula has an elevation lower than 1.5 meters above sea level, and a majority of Alligator River National Wildlife Refuge is lower than 1.0 meter (Alion Science and Technology, 2009). To make matters worse, the North Carolina coastline experiences more hurricanes than any other Atlantic coast state except for Florida, which could lead to excessive erosion and storm flooding (Darnell, 2008), and the peninsula's complex drainage canal and ditch system may further exacerbate the problem of rising sea levels (Gregg, 2010).

Due to this imminent inundation, wolves must either move themselves or be relocated to other habitat patches in order to escape extinction once again. However, many anthropogenic factors stand in the way of successful migration. Vehicle collision is one of the leading causes of death in red wolves (Fazio, 2007). With a large home range of approximately 90 km^2 for individuals and 125 km^2 for packs, and an expansive dispersal range of 35-45 km, large portions of contiguous land are needed for successful survival (Phillips et al. 2003). This is increasingly difficult to find with extensive urban development and habitat fragmentation in the southeastern United States.

The leading cause of death of the red wolf continues to be gunshot mortality (Fazio, 2007), which has increased since the North Carolina Wildlife Resources Commission passed a temporary law that allows night hunting of coyotes using a spotlight method. Because red wolves bear a similar resemblance to coyotes, they are often mistakenly shot and killed. Since the law passed in August of 2012, eight wolves have been illegally killed by gunshot wound and their deaths are currently under investigation by the U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service, 2012). The red wolf also has a history of human conflict leading to mortality due to livestock predation (Red Wolf Coalition, 2013). Table 1 shows causes of all deaths from 2010 to present, as collected by the U.S. Fish and Wildlife Service (2013).

Due to the increased likelihood of mortality with greater proximity to humans, migration to habitat should take place as far away from anthropogenic factors as possible. Rather than analyzing how these factors may impact landscape connectivity, however, past red wolf research has focused primarily on identifying key habitat areas for reintroduction. The question of how migration or movement to or from these reintroduction sites will occur has yet to be answered. With sea level rise, the ability to migrate either naturally or with support of wildlife managers will be an important key to survival.

One of the main recommendations for future actions as proposed by the U.S. Fish and Wildlife Service's five year status review of the red wolf states: "*Identify and evaluate land areas in red wolf historic range that could be considered for potential establishment of second and third wild red wolf populations. Examine biological and human factors important in identifying new restoration locations* (Fazio, 2007)". To aid in this effort, my objective is to look at the current distribution of red wolves and determine how they might move through the landscape to future habitat areas. The main variables that can affect migration and connectivity in this analysis include sea level rise and urban development, which is composed of road density, housing density, and future urban growth. Because sea level rise and urban growth will continue to reduce possible migration corridors and suitable habitat into the future, connectivity was analyzed for the years 2010 and 2050 to determine which pieces of land should have protection priority to allow for easier natural migration of the species.

Study Area

The Albemarle Peninsula is the largest peninsula in North Carolina and is located on the northeast coast of the state. Home to several wildlife refuges and reserves (Alligator River National Wildlife Refuge, Mattamuskeet National Wildlife Refuge, Swanquarter National Wildlife Refuge, Pocosin Lakes National Wildlife Refuge, Palmetto-Peartree Reserve, Emily and Richardson Preyer Buckridge Coastal Reserve), the ecosystem surrounding the peninsula is the third largest estuary system in North America creating habitat for estuarine-dependent species (Epperly, 1984).

Located on the easternmost portion of the peninsula is Alligator River National Wildlife Refuge. Encompassing almost 154,000 acres (Gregg, 2010), the refuge is home to many of the wild red wolves as well as many other species including black bears, bobcats, red-cockaded woodpeckers, and migrating neotropical birds. The refuge receives approximately 45,000 visitors annually, a majority of whom visit simply to experience the wildlife that lives there (U.S. Fish and Wildlife Service, 2013).

Containing the habitat patch that the wolves will move from, or the source patch, the Albemarle Peninsula and Alligator River National Wildlife Refuge will receive special attention in this analysis. However, due to the expansive range and migration ability of the wolves, the study area under examination consists of the entire state of North Carolina. The habitat patches, from which to determine connectivity, are located throughout the state from the coastal region to the mountains.

Methods

Because the red wolf is a habitat generalist (Chadwick et al., 2010), meaning it has no specific habitat preferences, running an analysis on habitat connectivity can be extremely difficult. The first step in this analysis was to examine the existing habitat range to determine if any preferential information could be inferred from the habitat currently being used. The historic habitat range was also analyzed in this case - considering they used to live throughout the entire southeastern United States, they can likely live in any environment with a high prey population. If habitat preferences had been found, a traditional connectivity analysis could have been used, prioritizing land type and habitat that red wolves favor. However, due to the lack of data collected prior to extinction, few habitat preferences are known. Therefore the connectivity analysis was run using a cost layer created from environmental and anthropogenic variables that the wolf will likely avoid when moving through the landscape. Connectivity was then calculated between the source patch on Albemarle Peninsula and the selected protected areas that served as potential habitat patches. This connectivity analysis was run in Arc GIS v. 10.1 (ESRI, 2012) using the state of North Carolina as the study area. A 30 by 30 meter cell size was used, and the North America Datum calculated in 1983 and Albers coordinate system was used as the projection.

Habitat Patches

Protected areas were extracted from a layer from the USGS Protected Areas Data Portal for North Carolina (USGS, 2012). Red wolves have a large home range and need expansive areas of contiguous land for habitat, therefore all protected areas with an area of 5000 acres or greater were selected. These selected patches were then clustered with other protected areas that shared the same border. Protected areas that did not share a border were also clustered together if they were within 500 meters of each other. Protected areas that were within sea level inundation range in 2050 were excluded, with the exception of Marine Corps Base Camp Lejeune, which will only experience slightly higher levels of inundation in 2050. Protected areas that are mostly waterways, including Jordan Lake, Falls Lake, the W. Kerr Scott Reservoir and the John H. Kerr Reservoir, were also excluded giving a total of 33 habitat patches (numbered 1-34 with value 13 missing) throughout the state. These represent the possible reintroduction habitat patches for the red wolf. Species distribution modeling was considered as part of the analysis to identify suitable relocation sites based on habitat preference. However because the red wolf is a habitat generalist and limited information exists about habitat uses outside of the Albemarle Peninsula, there was not enough solid information to construct a reliable model.

Sea Level Rise

Sea level rise was modeled using methods borrowed from the paper "Raster modelling of coastal flooding from sea-level rise" (Poulter & Halpin, 2008). Using a National Elevation Dataset (NED) from the National Hydrography Dataset (USGS, 2012), all cells below a certain elevation threshold were selected, creating a bathtub model of sea level rise. Next, cells were chosen only if they were connected to a shoreline layer, and subsequent cells were added if they met the threshold and were connected to other water cells. The cells could be connected in one of eight ways: up, down, left, right, or any of the four corners. The threshold values were chosen based on a sea level rise model created and calculated by The Nature Conservancy (Pearsall, 2011). According to the model, sea level rise in 2050 will be approximately 0.38 meters above the current level, and this value was used as the elevation threshold. Canals and ditches were cut into the NED layer prior to running any analysis, as this may increase the likelihood of land inundation. A GIS layer containing the location of canals and ditches was obtained from the National Hydrography Dataset from USGS (2012), and the elevation was reduced by 3 meters in locations where these water features are present.

Cost Surface

A cost surface was created by adding several variables to the ArcGIS Weighted Overlay tool. This cost surface represents the cost that a species incurs when moving from one place to another through the landscape. Typically, the higher the threat a certain variable poses, the higher the cost to the animal, such as road crossings or large bodies of water. Low cost indicates little to no threats posed to the animal, and may be composed of variables such as forest cover or low human population. The cost typically depends on species preference of habitat. However, since little is known about red wolf habitat preference, this analysis was largely focused on variables the species will avoid when traveling.

NLCD and Slope

One variable that went into this cost surface was a 2006 USGS National Land Cover Dataset (NLCD) (Fry et al. 2011). Each land cover type was given a cost score, with water bodies and urban development given the highest scores and forested and grassland areas given the lowest scores. High intensity urban development was given a score of "No Data", suggesting that travel through this region would be strictly avoided. Information on habitat preference was gathered from several studies (Fazio, 2007; Karlin, 2011; Hinton & Chamberlain, 2010; Vaughan & Kelly, 2011), but this information is limited given that all available data has been collected from the restricted habitat on Albemarle Peninsula. Dr. Ron Sutherland, who is conducting a similar study with Wildlands Network in the southeast region, collected expert opinion data concerning red wolf NLCD habitat preference from red wolf biologists. Permission was granted to use these numbers, and they were included in the cost analysis. Slope was also used as a variable, and was derived from the NED using the Slope tool. Past research has shown that gray wolves prefer habitat with and move easier through slopes of less than 20^{o} (Callaghan & Wierzchowski, 1999). Therefore areas with lower slopes were given lower cost scores than areas with higher slopes.

Housing Density

A housing density dataset created by R.B. Hammer and V.C. Radeloff at the University of Wisconsin was used as another variable in the cost surface analysis (Hammer, R.B. & Radeloff, V.C., 2005). The dataset included GIS layers from 1940 to 2030 in ten year increments with values ranging from 0 (undeveloped, private, rural land) to 10 (urban, built up, few to no housing units). This data was used to calculate the mean housing density for each census tract in North Carolina (U.S. Census Bureau, 2010) using the Zonal Statistics tool for each year of the dataset. These values were put into a Microsoft Excel (2007) spreadsheet, and values for 2050 were then projected using the linear trend function. These projected values were put into GIS using the Reclass tool, and census tracts with higher housing density means were given a higher cost value than those with lower housing density means.

Table 2 - Model variables, cost values, and % influence used to create the cost surface with the weighted overlay tool.

Raster	% Influence	Field	Scale Value
NLCD	35	**VALUE**	
		Water	10
		Open Development	5
		Low Development	5
		Medium Development	10
		High Development	No Data
		Barren Land	5
		Deciduous Forest	1
		Evergreen Forest	1
		Mixed Forest	1
		Shrub/Scrub	1
		Grassland/Herbaceous	1
		Pasture/Hay	2
		Cultivated Crops	1
		Woody Wetlands	1
		Emergent Herbaceous Wetlands	5
Slope	10	**VALUE**	
		1 (0-10^o)	1
		2 (10-20^o)	1
		3 (> 20^o)	5
Road Density	20	**VALUE**	
		1 (0-0.25 km/km^2)	1
		2 (0.25-0.5 km/km^2)	4
		3 (> 0.5 km/km^2)	10
Housing Density	10	**VALUE**	
		1 (All rural land to more than 80 acres rural I)*	2
		2 (40 to 80 acres rural land I)	4
		*3 (10 to 40 acres rural land II per unit**)*	6
		4 (All urban to 6.8 acres urban per unit)	8
Urban Growth	20	**VALUE**	
		*1 (0-10% chance of development***)*	5
		2 (1-20% chance of development)	6
		3 (20-50% chance of development)	8
		4 (50-70% chance of development)	10
		5 (70-100% chance of development)	10
		No Data	1
Sea Level Rise	5	**VALUE**	
		1	No Data
		No Data	1

* rural I refers to low intensity rural development
** rural II refers to high intensity rural development
*** a low chance of development means the land is already developed

Urban Growth

To model urban growth in the year 2050, a model created by the Biodiversity and Spatial Information Center at North Carolina State University in Raleigh (Terando et al., unpublished) was used. This SLEUTH model, named for the inputs of the model (slope, land use, excluded, urban, transportation, and hillshade), consists of a data layer showing the probability of future urban development with values ranging from 1 (meaning no change, already developed) to 1000 (meaning a 100% probability of future development). The data layer for the year 2050 was used in the future cost surface analysis. The data layer for the year 2010 was used for the current cost surface analysis, not because it provided any new urban areas not already classified as "developed" by the NLCD layer, but because it created a weighted overlay output similar to the one created for 2050. Areas with lower probability of development were given a moderate cost value, as these areas are likely already highly developed, while the areas with a higher probability of development were given a high cost value.

Road Density

The last cost surface variable was road density. A primary and secondary road routes layer (NCDOT, 2013) was downloaded from the NC Department of Transportation website that includes the following road classes: Interstate, US Route, NC Route, secondary road, ramp, rest area, projected highway, local, parks, and Federal. For the purposes of this study, only major roads and highways need to be considered, therefore Interstate, US route, NC route, and Federal roads were used in the analysis for 2010, while the analysis for 2050 also included projected highways. To calculate the density of roads in kilometers per square kilometers, the GIS Kernel Density tool was used. Past research shows that red wolves prefer areas with road density less than 0.18 km/km^2 (Karlin, 2011), therefore areas with lower road density were given lower cost scores while areas with high road density were given higher cost scores.

Connectivity

Each variable was put into the Weighted Overlay tool and given a weight of importance to the model (see table 2). The NLCD land cover layer was given the highest weight of importance, contributing an influence of 35% to the model, because land cover type will likely influence how the wolves will move through the landscape rather than represent avoidance to obstacles or threats. Due to the high cost of anthropogenic factors to movement, urban growth and road density were given the next highest influence to the model, each with a 20% influence. Housing density was given a lower value, only 10% influence to the model, because the original data was segmented into large census tracts and transformed into mean values. This data manipulation was necessary for simplified extrapolation, however it may have introduced some error. Slope was also given a value of 10% influence, and sea level rise was given a 5% influence to the model.

Habitat Patch Number	Protected Area Name	Habitat Patch Area (acres)
1	Nantahala National Forest Great Smoky Mountain National Park Eastern Cherokee Indian Reservation Southern Nantahala Wilderness Joyce Kilmer-slickrock Wilderness	644100.15
2	Nantahala National Forest	125322134.8
3	Nantahala National Forest Pisgah National Forest Gorges State Park	1030239069.56
4	Dupont State Forest	41605457.47
5	Green River State Game Land	47175560.2
6	South Mountains Game Land	147102045.8
7	Pisgah National Forest	128179988.6
8	Pisgah National Forest	56494100.8
9	Pisgah National Forest	292246872.4
10	Nantahala National Forest	26968270.87
11	Pisgah National Forest	806871692.6
12	Buffalo Cove Game Land	22856258.25
14	Stone Mountain State Park Thurmond Chatham Game Land	59078298.67
15	Hanging Rock State Park	20865913.51
16	Uwharrie National Forest	21507054.71
17	Alcoa State Game Land Uwharrie National Forest	104567015.8
18	Pee Dee National Wildlife Refuge	30437750.39
19	Camp Mackall Sandhills State Game Land	209949077.04
20	Pope Air Force Base Fort Bragg Military Reservation Rockfish Creek State Game Land	633204341.01
21	Suggs Mill Pond State Game Land Bushy Lake State Natural Area	54342929.46
22	Bladen Lakes State Forest Jones Lake State Park Turnbull Creek Educational State Forest	117884965.1
23	Columbus County State Game Land	24262053.45
24	Green Swamp Preserve Green Swamp State Game Land	119624222.6
25	Military Ocean Terminal Sunny Point	36187735.66
26	Bear Garden Tract Southwest Ridge Preserve Angola Bay Tract Holly Shelter State Game Land Angola Bay State Game Land	506978629.04
27	Camp Lejeune MCAS New River	576452612.9
28	Croatan National Forest MCAS Cherry Point	642569364.1
29	Van Swamp State Game Land	22321600.15
30	Devil's Gut Preserve Roanoke River	41586226.97
31	Chowan Swamp State Game Land Chowan Swamp State Natural Area	81262146.05
32	Great Dismal Swamp National Wildlife Refuge Dismal Swamp State Natural Area	158242588.3
33	Shearon Harris State Game Land Chatham State Game Land	46095659.32
34	William B. Umstead State Park	22640644.63

Table 3 - Habitat patches included in the analysis and the protected areas that are included in them. The areas listed were calculated for the entire habitat patch.

The resulting cost surface shows the cost of movement through each cell of the map. This was used to produce a least cost path analysis, using the cost path tool, from the Alligator River National Wildlife Refuge in the 2010 analysis, and a more inland portion of the wolf's habitat (McKerrow et al. 2006) on the Albemarle Peninsula in the 2050 analysis, to all other habitat patches in the state (table 3 lists all patches). A least cost path consists of a single-cell wide line showing the best possible route for an animal to take, incurring the least cost as it moves from one patch to another. However, while least cost paths provide a nice visual of how the animal might move, the probability of the animal taking that exact route is almost zero. Therefore, least cost corridors were also created connecting the source patches to all other habitat patches. This was done using the Corridor tool in GIS. Contrary to the least cost path analysis, the corridor tool creates a larger width path in which the animal is likely to move. Within this path are various costs of movement, with the lower cost areas given as a higher likelihood of movement than the higher cost areas. Using this tool, it is easier to see the variation in how an animal may move through the landscape while still encountering the smallest amount of cost or threat.

To create the corridor, a cost surface must be created from both the source patch and the habitat patch. The corridor tool combines these cost layers to determine connectivity between the two patches. To create a corridor, however, a threshold must be chosen to determine how much cost should be included in the corridor. To determine this threshold, the lowest value of the cost layer for the patch in question was examined and 5,000 cost distance units were added to that value. This threshold value was calculated for each patch, and was used in the corridor tool.

Least cost corridors were closely examined for each of the final selected habitat patches, and also for Fort Bragg and two regions of Pisgah National Forest. Examining corridors to these last three patches will give a better idea of how migration will change throughout the state. Current corridor results were compared to future results, and bottlenecks were identified in these selected corridors. The bottlenecks represent areas where transportation may be particularly difficult due to barriers in the landscape, and protection or management efforts may be necessary to assure successful movement in the future through these locations. Possible causes of these bottlenecks were then identified so that mitigation or management efforts can be focused on these sources.

Least Costly Habitat Patches

The minimum cost distance from the source patches on Albemarle Peninsula to each habitat patch was calculated using the zonal statistics tool. These cost distances were taken from the cost layer for 2010 and 2050. The five patches with the lowest cost distance from the source patches were highlighted. Each patch was also buffered with a Euclidean distance of 1.0 kilometer, and the mean cost in this buffered area was calculated to represent how each patch is impacted by possible threats. Finally, the least cost paths were measured to determine how many meters the animal would have to travel to get to each habitat patch, given that it chooses to migrate along this path. This was done by calculating the Euclidean distance to each patch using the least cost path as a mask. The minimum distance to each patch was then calculated using the zonal statistics tool. Again, the five patches with the shortest route to the source patches, as well as the five patches with the lowest mean buffer cost, were highlighted as patches of interest. The patches that met all three criteria, or two out of three of the criteria, were chosen as habitat patches of interest. Table 4 shows the values of these criteria for each patch.

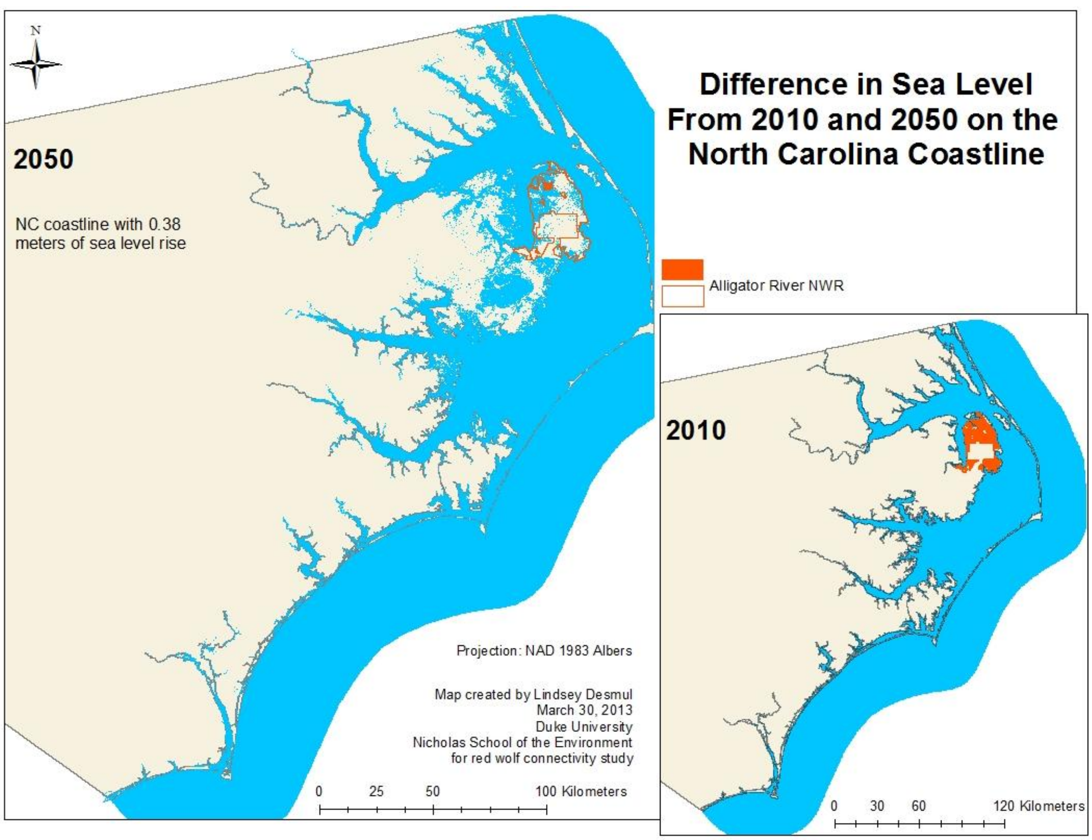

Figure 2 - Sea level rise in 2050 compared to current levels. Alligator River, outlined in red in 2050, appears to be highly disconnected from the mainland of North Carolina due to high levels of inundation in 2050.

Results

Sea Level Rise

Figure 2 shows the North Carolina coastline with an increase in sea level of 0.38 meters by the year 2050. Looking at this figure, it appears that the Albemarle Peninsula is the only area in North Carolina that will experience vast inundation by mid-century. According to The Nature Conservancy, this model is relatively conservative compared to other popular sea level rise models and it is likely that the coastline will change even more by 2050, reducing the possibility of natural migration substantially. This poses the largest problem for the wolves currently residing in Alligator River National Wildlife Refuge, as they will undoubtedly be almost completely inundated by 2050, highly restricting connectivity from the refuge to the mainland. Other inland areas on the peninsula, such as the Pocosin Lakes Wildlife Refuge, will be less affected by mid-century, but will likely experience inundation by 2100.

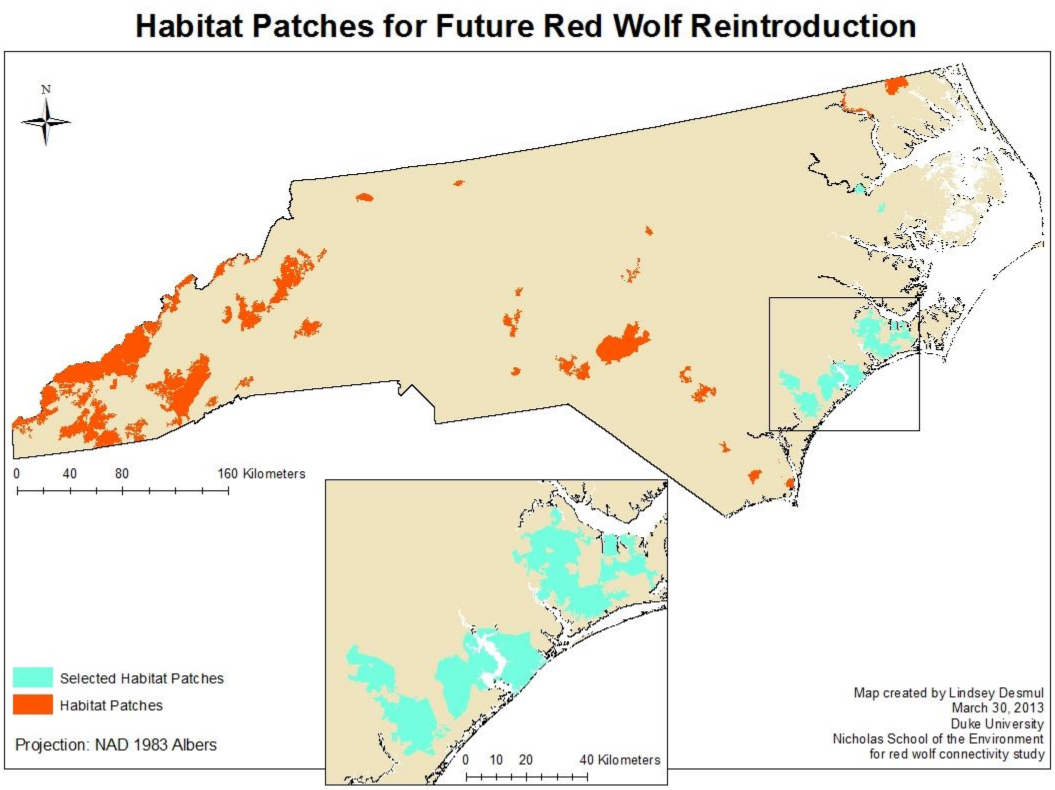

Figure 3 - Selected habitat patches for future red wolf reintroduction. Five total patches were selected as being suitable for natural reintroduction (without the aid of managers) of red wolves by the year 2050. The effect of sea level rise on Camp Lejeune can be seen in the map zoom-in.

Habitat Patches

All of the selected habitat patches, shown in figure 3, are located in the coastal region of North Carolina, which may pose a risk in the future. The sea level rise model for 2050 shows that sea level rise will not dramatically affect any of these patches, with the exception of Camp Lejeune, which appears to be slightly more inundated by the series of bays in the New River inlet. However, this may not pose a problem to the red wolf. As proven by the pack of wolves reintroduced to Bulls Island off the Albemarle Peninsula in 1987, red wolves are strong swimmers and will swim through salt water to get to more suitable habitat (U.S. Fish and Wildlife Service, 1999). However, the Bull's Island pack was on an island rather than the

Habitat Patch Number	2010 Mean Cost in 1 km Buffer	2050 Mean Cost in 1 km Buffer	*Difference in Buffer Cost from 2010 to 2050*	2010 Minimum Distance (in m) to Patches via Least Cost Path	2050 Minimum Distance (in m) to Patches via Least Cost Path	*Difference in Distance to Patch from 2010 to 2050*	2010 Minimum Cost of Travel to Patches	2050 Minimum Cost of Travel to Patches	*Difference in Minimum Cost of Travel from 2010 to 2050*	Patch Area (Acres)
1	2.5	2.9	0.5	622302.2	585929.2	-36373.0	1267691.0	1297559.8	29868.8	644100.2
2	2.5	3.2	0.8	637636.9	603357.8	-34279.2	1348053.5	1400043.0	51989.5	125322134.8
3	2.5	3.0	0.5	581112.1	544731.8	-36380.3	1225346.0	1259955.5	34609.5	1030239069.6
4	2.1	2.4	0.3	581459.8	545243.8	-36215.9	1224962.1	1290190.1	65228.0	41605457.5
5	2.9	3.3	0.4	550789.0	514933.6	-35855.4	1160506.0	1195627.4	35121.4	47175560.2
6	2.1	2.1	0.1	491979.9	457661.2	-34318.8	1032101.1	1062975.3	30874.1	147102045.8
7	2.1	2.2	0.1	530926.3	494322.4	-36603.8	1043318.2	1072625.1	29306.9	128179988.6
8	2.1	2.1	0.1	557749.6	521363.6	-36385.9	1124585.6	1143584.1	18998.5	56494100.8
9	2.3	2.4	0.1	582639.8	545974.0	-36665.8	1175994.3	1206109.3	30115.0	292246872.4
10	2.8	3.3	0.5	653164.3	616517.5	-36646.8	1358947.8	1390545.0	31597.3	26968270.9
11	2.5	2.7	0.2	493455.5	456907.4	-36548.1	966546.7	986414.8	19868.1	806871692.6
12	2.0	2.0	0.0	482304.8	445757.1	-36547.7	941935.7	960317.2	18381.5	22856258.3
14	2.2	2.4	0.2	443671.1	407071.8	-36599.3	833925.8	851912.1	17986.3	59078298.7
15	2.2	2.4	0.2	374992.4	338291.1	-36701.3	682436.8	696231.1	13794.3	20865913.5
16	2.1	2.2	0.1	338154.9	302982.8	-35172.1	667974.4	692086.1	24111.8	21507054.7
17	2.3	2.4	0.1	353099.9	306583.4	-46516.4	675199.3	698722.1	23522.8	104567015.8
18	2.1	2.2	0.1	356866.3	322325.7	-34540.6	649918.4	702416.5	52498.1	30437750.4
19	2.2	2.3	0.1	309601.4	277430.9	-32170.5	547109.7	598188.8	51079.1	209949077.0
20	3.1	3.7	0.6	256829.8	222798.0	-34031.8	473439.8	507069.2	33629.4	633204341.0
21	1.7	2.0	0.3	245147.6	214160.2	-30987.3	402921.9	442936.7	40014.8	54342929.5
22	1.9	2.0	0.1	233992.6	204870.6	-29122.0	390016.4	429805.3	39788.8	117884965.1
23	2.1	2.6	0.5	256713.4	230967.5	-25745.9	416531.2	469712.7	53181.5	24262053.5
24	1.6	2.2	0.6	256909.1	233212.8	-23696.3	430617.1	481596.9	50979.8	119624222.6
25	2.5	3.1	0.6	247948.6	229817.7	-18130.9	464202.5	524038.3	59835.8	36187735.7
26	1.7	1.9	0.1	186279.1	160143.2	-26135.9	311160.8	338093.3	26932.5	506978629.0
27	3.0	3.4	0.4	147084.3	132215.5	-14868.7	280229.6	316122.9	35893.3	576452612.9
28	2.3	2.8	0.4	121385.8	107382.4	-14003.3	227814.5	270637.0	42822.5	642569364.1
29	1.8	1.8	0.0	56965.8	20352.0	-36613.8	61995.7	22170.6	-39825.1	22321600.2
30	1.6	1.9	0.3	72358.5	35739.0	-36619.5	87222.7	60654.8	-26567.9	41586227.0
31	1.6	2.2	0.6	109036.2	NA	NA	196720.1	NA	NA	81262146.1
32	1.5	2.1	0.5	86099.7	NA	NA	240291.3	NA	NA	158242588.3
33	2.6	2.7	0.1	249227.7	213287.3	-35940.3	473477.8	493364.3	19886.5	46095659.3
34	5.2	5.7	0.4	238690.3	202094.8	-36595.5	437764.5	434408.2	-3356.3	22640644.6

Table 4 - Mean cost within 1 km of each patch, minimum cost of movement, and minimum distance of movement to each habitat patch from source patches in 2010 and 2050. The highlighted patches were those chosen as optimal reintroduction sites for 2050 - those with the lowest values in each category.

mainland, which may increase their willingness to swim to different areas. Other studies show that, when given the choice, wolves will typically avoid water (Vaughan & Kelly, 2011).

The patches closest to the current red wolf distribution, with the least mean cost in the surrounding buffer, and the lowest minimum cost of travel from the source patches included Camp Lejeune (patch 27), Croatan National Forest (patch 28), a cluster of game lands (patch 26), Van Swamp State Game land (patch 29), and Devil's Gut Preserve near Roanoke River (patch 30). Two other patches in the northeastern portion of the state also seemed to fit the criteria, Chowan Swamp State Game land (patch 31) and Great Dismal Swamp National Wildlife Refuge (patch 32), except they will be cut off from the mainland of North Carolina with sea level rise by 2050. Since the analysis was not conducted for both North Carolina and Virginia, it is unknown how far north the land will be inundated. It is possible that the wolves will be able to travel north into Virginia and then southeast to reach these locations. However, due to the large amount of uncertainty, these patches were only included in the analysis for the year 2010.

As can be seen in table 4, patch 29 has the lowest mean buffer cost in the year 2050, as well as the shortest distance from the source patches, and the lowest minimum cost of travel from the source patches. Unfortunately, it is also one of the smallest patches in the analysis. Patches 26 and 27 are amongst the lowest costs and shortest distance of travel for 2050 but not for 2010. Once again, patches 31 and 32 were not considered in the analysis for 2050.

Human Impact

Future changes in urban development, housing density, and road density were all approximations in this analysis taken either from models or from current data and extrapolated out to 2050. Even with these limitations, the cost layer produced from the analysis shows expansive growth outward from current cities and large highways, which follows the theory of urban sprawl. According to this analysis, most of the future urban growth will occur most heavily around the Triangle region, Charlotte, Greensboro, the Sandhills region, Asheville, and Wilmington, North Carolina. Areas not as heavily affected include the coastal region, areas

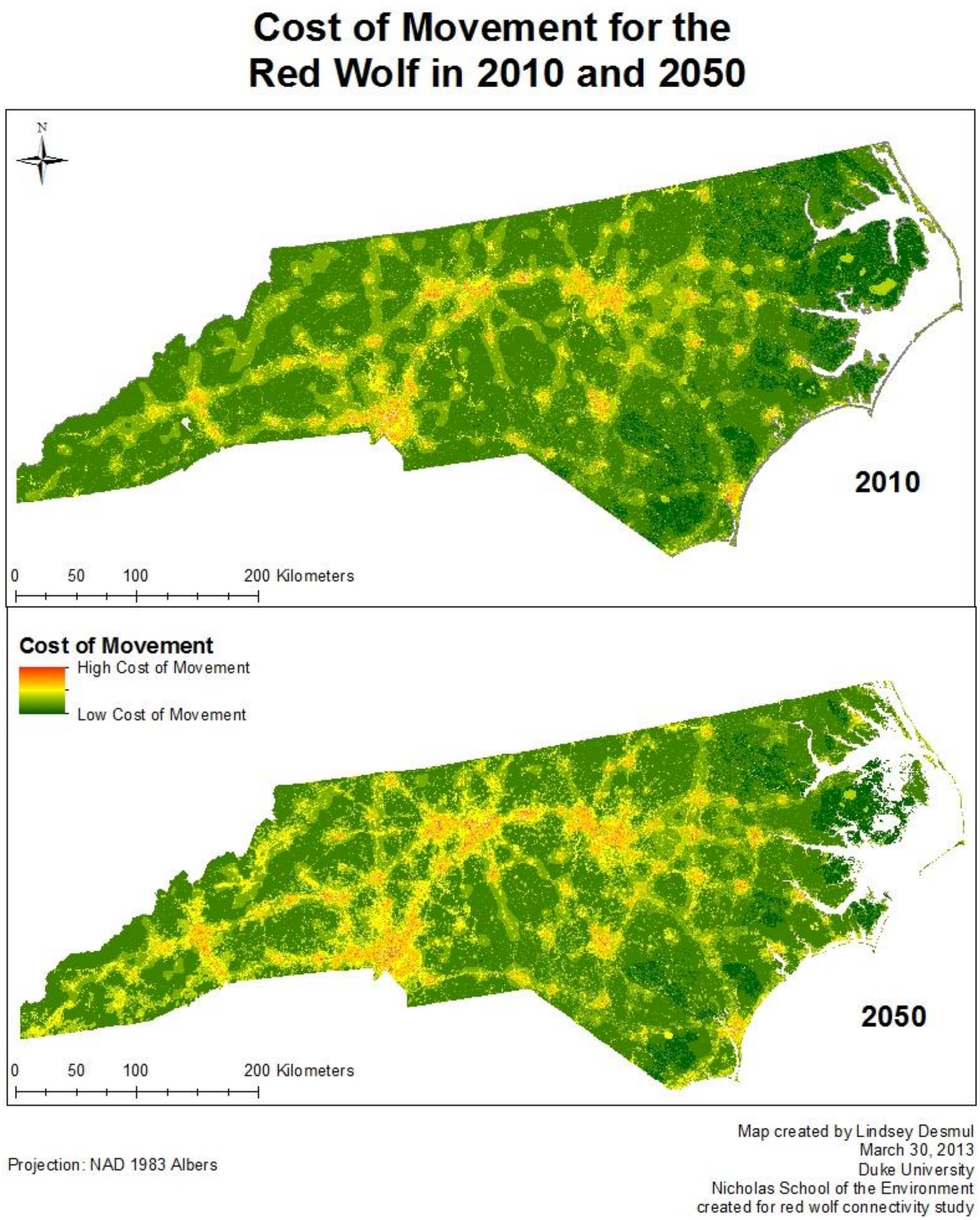

Figure 4 - Cost surface layers showing the cost of movement for the red wolf through the North Carolina landscape in 2010 and 2050. This map highlights urban areas such as the Triangle and Charlotte regions as representing some of the highest costs to movement to the wolf in both 2010 and 2050.

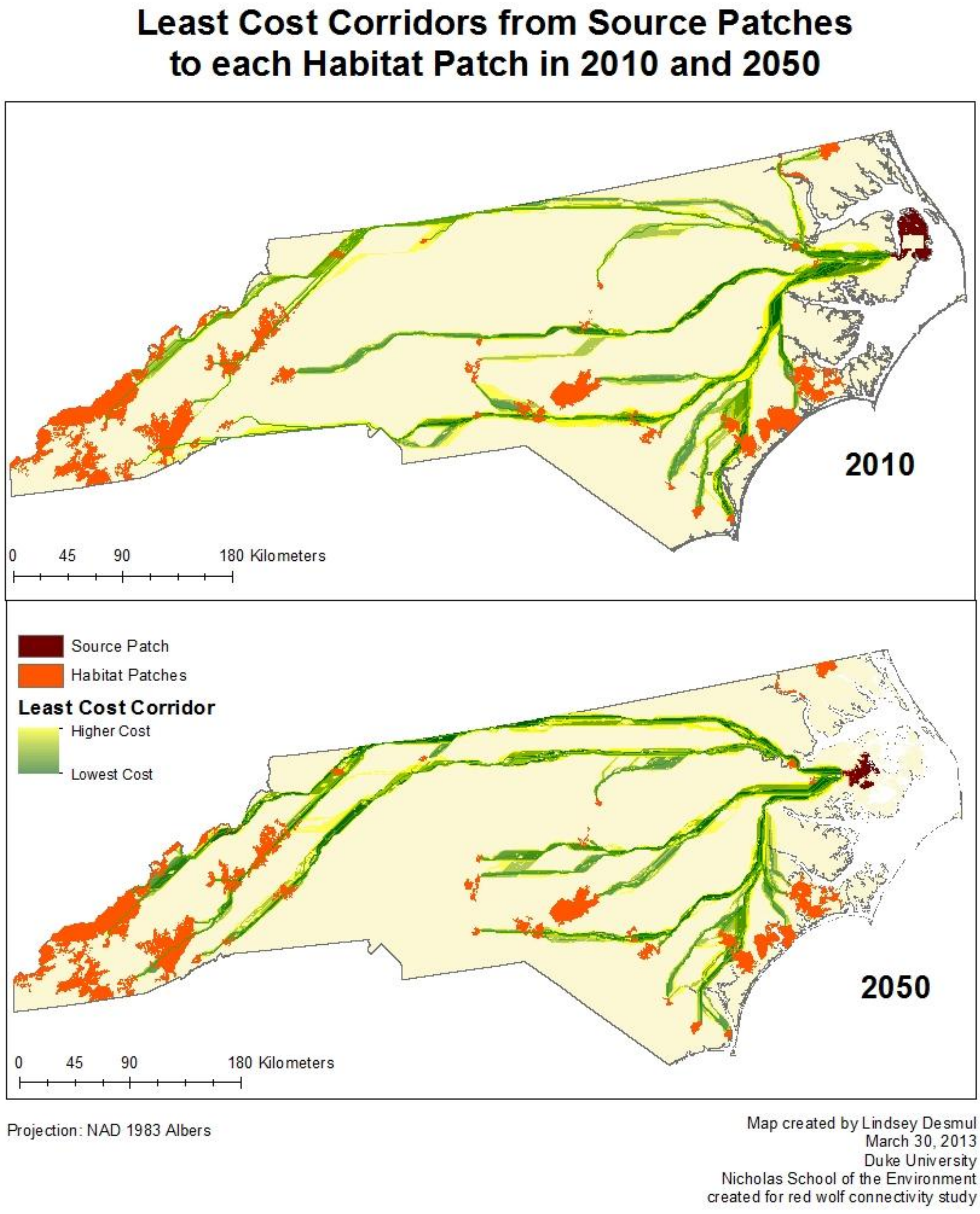

Figure 5 - Least cost corridors from source patches to habitat patches in 2010 and 2050. These corridors show how red wolves would move across the landscape if they chose the path that would incur the least amount of physical cost to them.

south of Fayetteville, and the northernmost portion of the state (see figure 4). These areas appear to remain relatively unchanged and open to easier migration. Looking at the least cost corridors to each habitat patch (figure 5), it appears the routes that cross through the middle of the state in 2010 no longer do so in 2050, likely due to this increase in urban development. The habitat patches with the largest increase in surrounding cost include Fort Bragg (patch 20) and Nantahala National Forest (patch 2). Fort Bragg is located near Fayetteville, NC, which has recently experienced an urban growth boom due to an insurgence of military personnel. It is unclear whether this growth will continue or remain stable, as Fort Bragg is the largest military base in the country and one of the largest military installations in the world (GlobalSecurity, 2011), however the population surrounding the base depends largely on current war efforts and therefore may be reduced in the future.

While Nantahala National Forest is in close proximity to other vast protected areas, it is also in the range of being affected by Asheville's future urban sprawl, making migration more difficult. However, the Nantahala National Forest is fairly close to a large cluster of protected areas, and if reintroduction is to be attempted in this region once more, it may be possible to create some greenways for the wolf to facilitate easier movement between the patches. Successfully reaching the mountains of North Carolina would require the wolf to either migrate northward first and then west, or it may require the assistance of wildlife managers for transportation. Considering the closest patch in the mountainous cluster is almost 500,000 meters (or 310 miles) away, this may be a difficult trek for wolves to make.

Least Cost Corridors

Least cost corridors were closely examined for each of the five chosen habitat patches in 2010 and 2050. Looking at the results, it does not appear that connectivity will change drastically by mid-century, especially for patches 29 and 30. However, in most of the corridors, bottleneck areas or barriers to migration can be seen to increase from 2010 to 2050. Patch 29 is the only patch with no visible barriers to transportation, likely due to its close proximity to the source patches (figure 6). The corridor to patch 30 only has a couple of barriers that differed

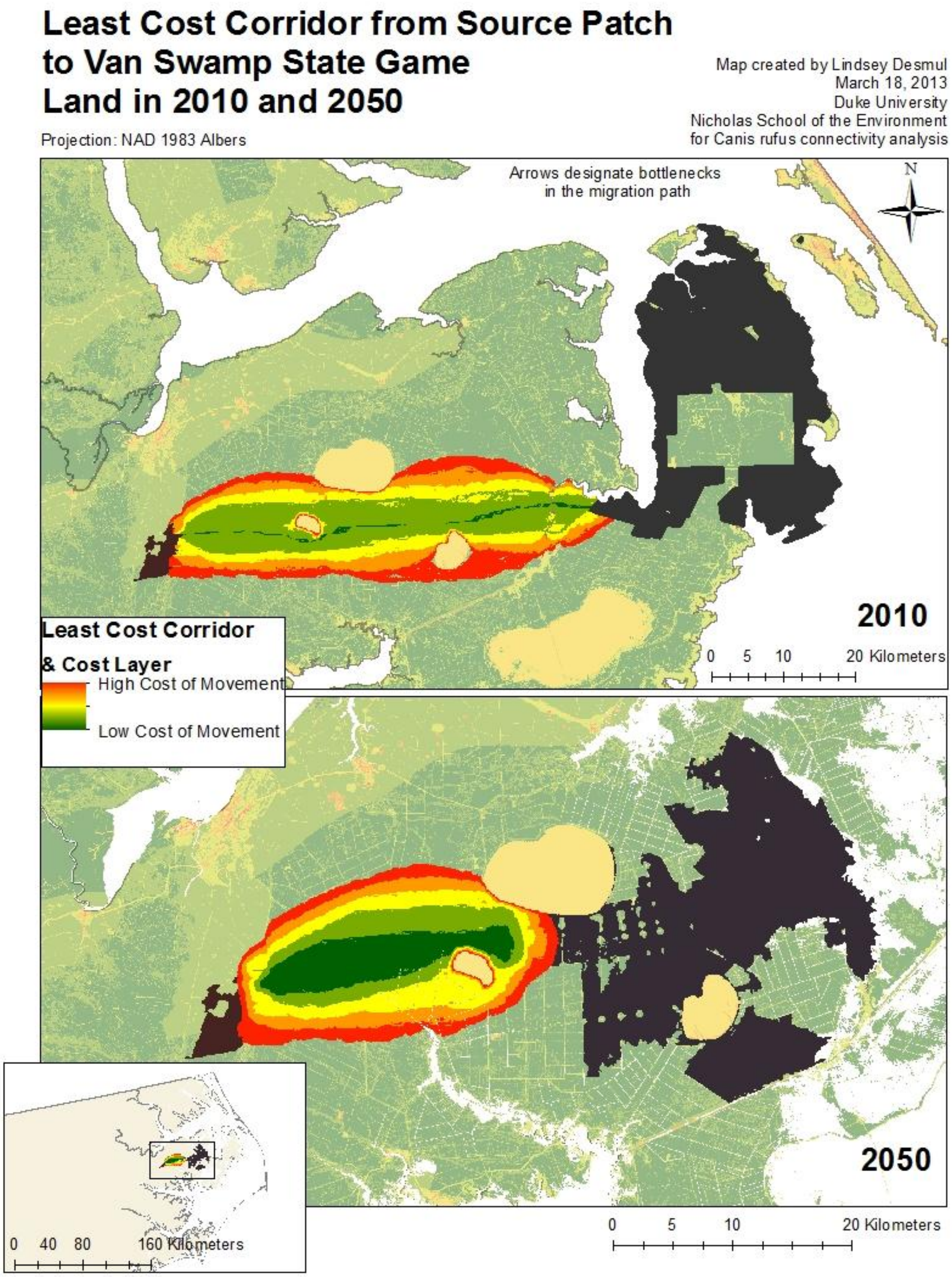

Figure 6 - Least cost corridor to Van Swamp State Game Land in 2010 and 2050. No barriers to migration can be seen in these corridors, likely because of the short distance of travel from the source patches to Van Swamp State Game Land.

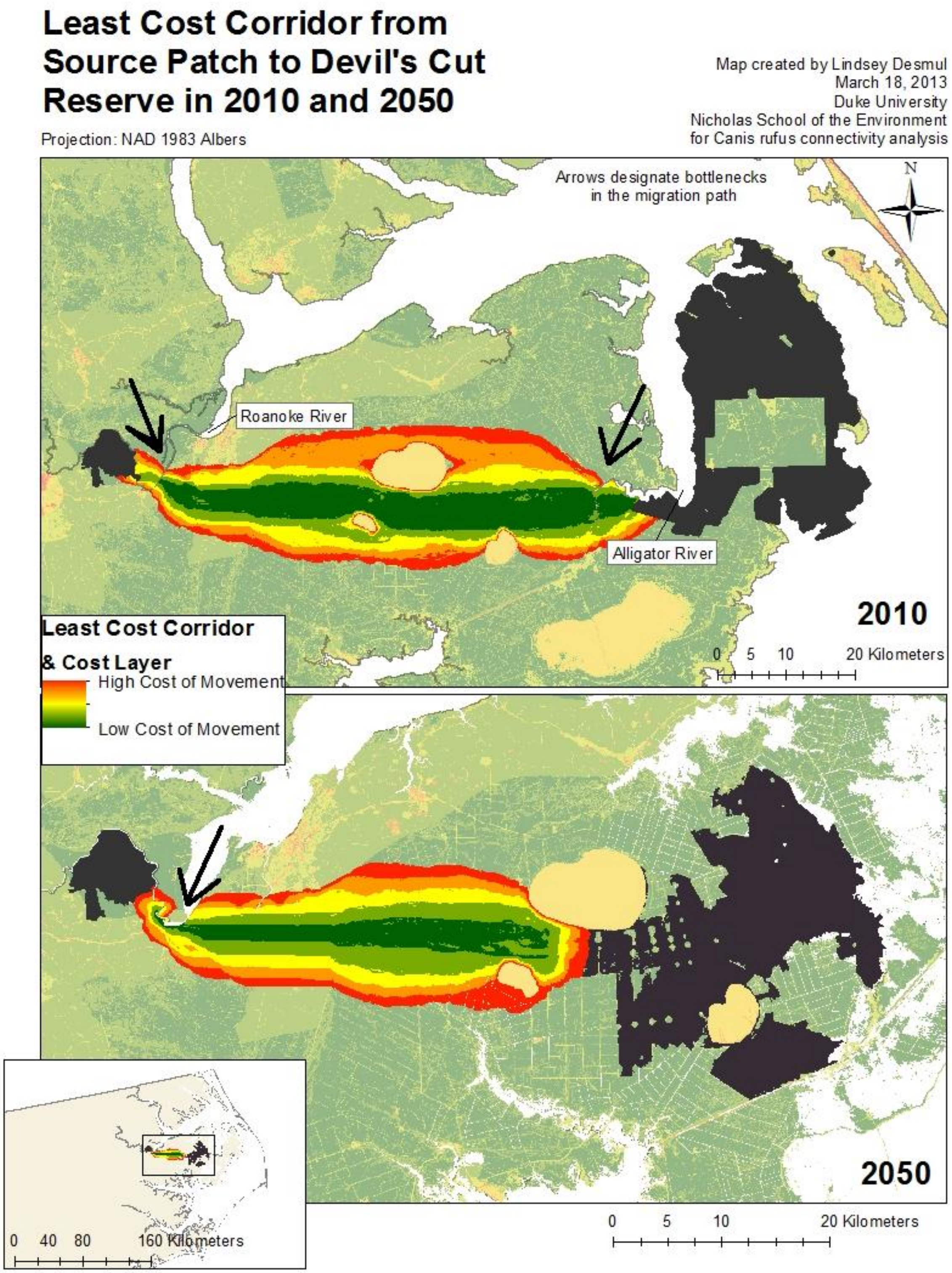

Figure 7 - Least cost corridor from the source patch to Devil's Cut Reserve in 2010 and 2050. Two barriers can be seen in 2010 - one from Roanoke River and one from Alligator River. Roanoke River also creates a barrier to migration in 2050.

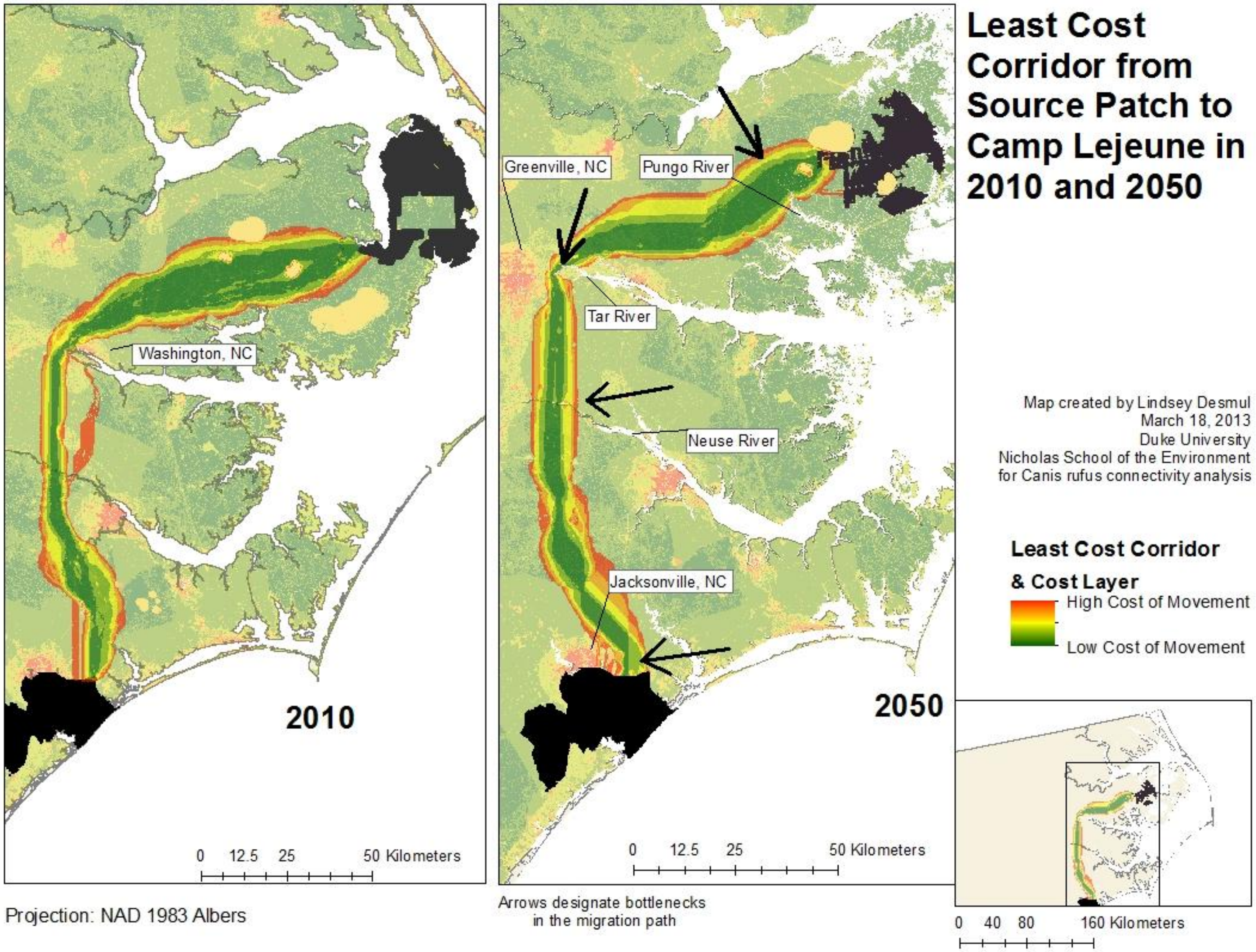

Figure 8 - Least cost corridor from the source patch to Camp Lejeune in 2010 and 2050. Urban barriers to migration include Jacksonville, Greenville, and Washington, NC. Natural barriers include the Pungo, Tar, and Neuse Rivers.

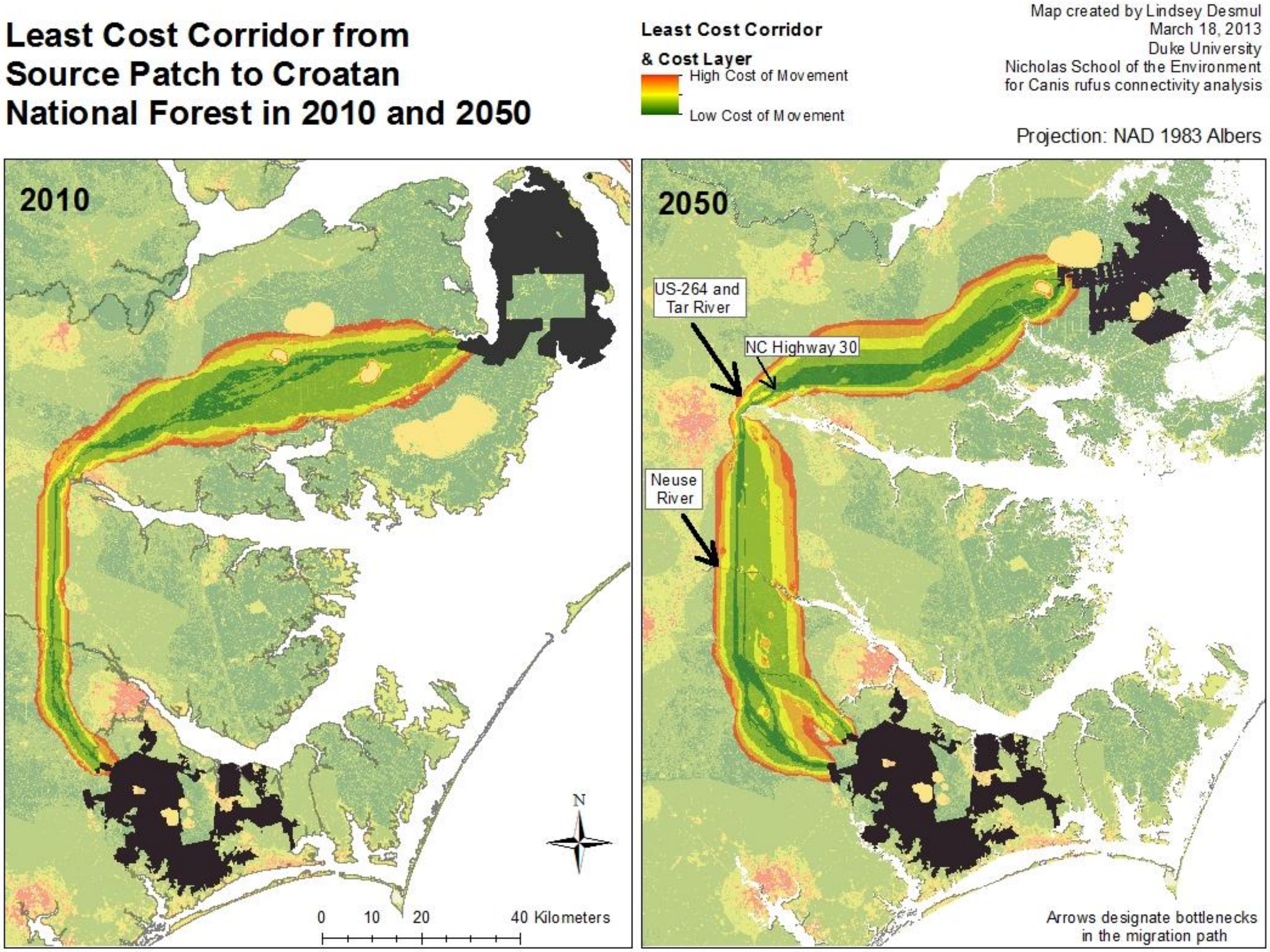

Figure 9 - Least cost corridor from source patch to Croatan National Forest in 2010 and 2050. Barriers to migration include NC Highway 30, US Route 264, and the Tar and Neuse Rivers.

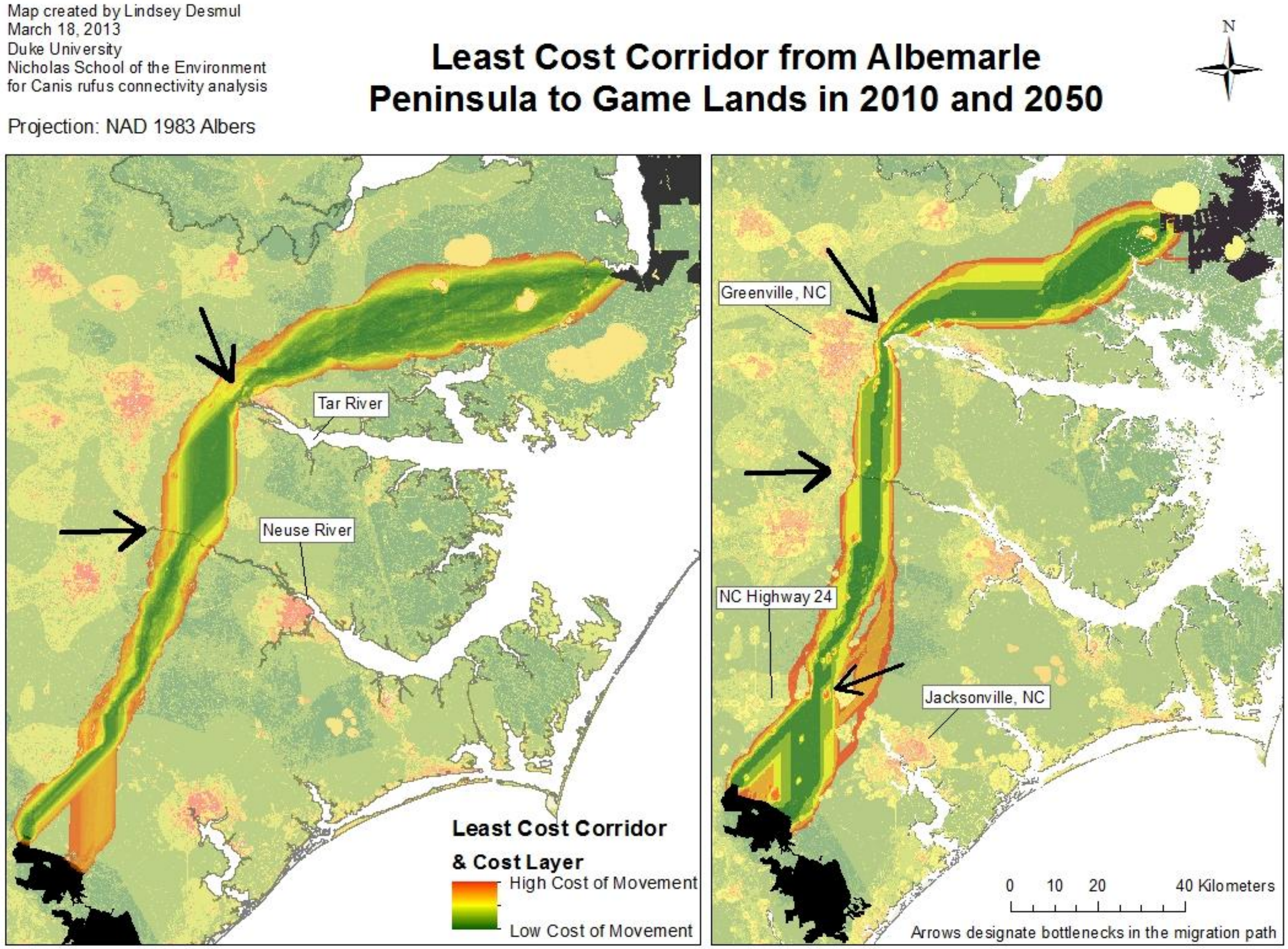

Figure 10 - Least cost corridor from source patch to game lands in 2010 and 2050. Barriers to migration include the Neuse and Tar Rivers in both 2010 and 2050, as well as NC Highway 24, and the towns of Jacksonville and Greenville, NC in 2050.

slightly between 2010 and 2050, and those barriers represent the wolves crossing the Roanoke and Alligator Rivers (figure 7). Patch 27 has barriers that also consist of river crossings; both the Pungo River and the Tar River in 2010 and 2050, and the Neuse River in 2050. However, there also seems to be a disturbance created by the projected development of Greenville and Washington, NC as well as Jacksonville, NC (figure 8). Patch 28 appears to be affected by transportation routes, including US-264 and NC Highway 30 in 2050 as well as the Tar and Neuse Rivers (figure 9). Patch 26 appears to have bottlenecks associated with crossing the Neuse River in 2010 and the Tar River in 2010 and 2050. These bottlenecks can also be loosely associated with a high future housing density and the presence of low intensity developed land

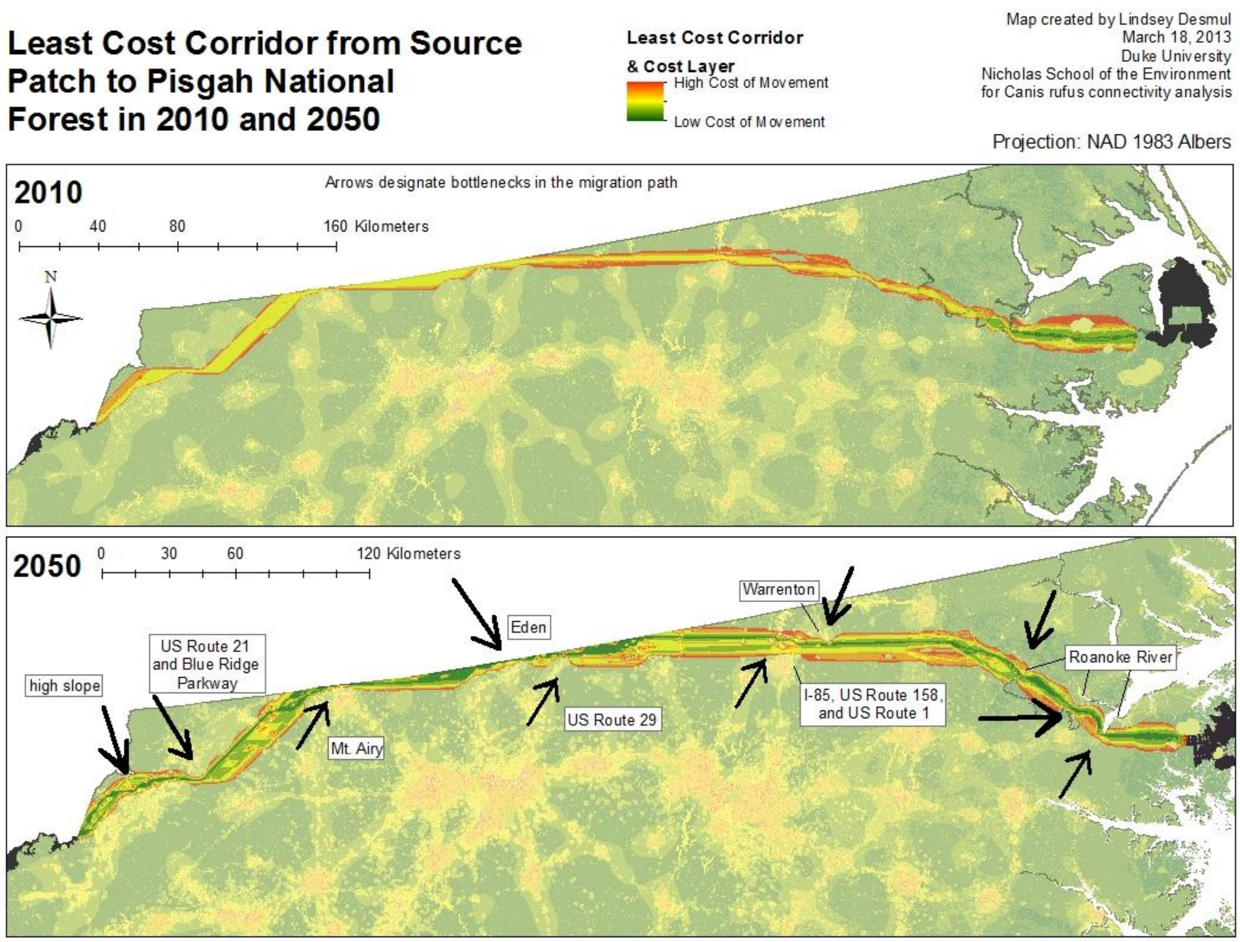

Figure 11 - Least cost corridor from source patch to Pisgah National Forest in 2010 and 2050. The Roanoke River acts as a large barrier to migration in 2010 and 2050. Other barriers include I-85, US Routes 1, 158, 29, and 21, and the towns of Warrenton, Eden, and Mt. Airy, NC.

including Greenville and Jacksonville, NC (figure 10). The barriers to the three other habitat patches, Fort Bragg and two patches in Pisgah National Forest, were also identified to determine what kind of obstacles the wolves will encounter when traveling further from their current location. The least cost corridors created for Pisgah National Forest show several different barriers due to the considerable distance from Alligator River. To patch 7, which is on the far western border of the state, environmental barriers include the Roanoke River and the steep slope of the mountains (figure 11). Anthropogenic barriers include the towns of Eden in both 2010 and 2050 and Warrenton and Mount Airy in 2050 as well as several highways (US-29, US-29, US-1, US-158, I-85, and the Blue Ridge Parkway). To patch 11, which is approximately

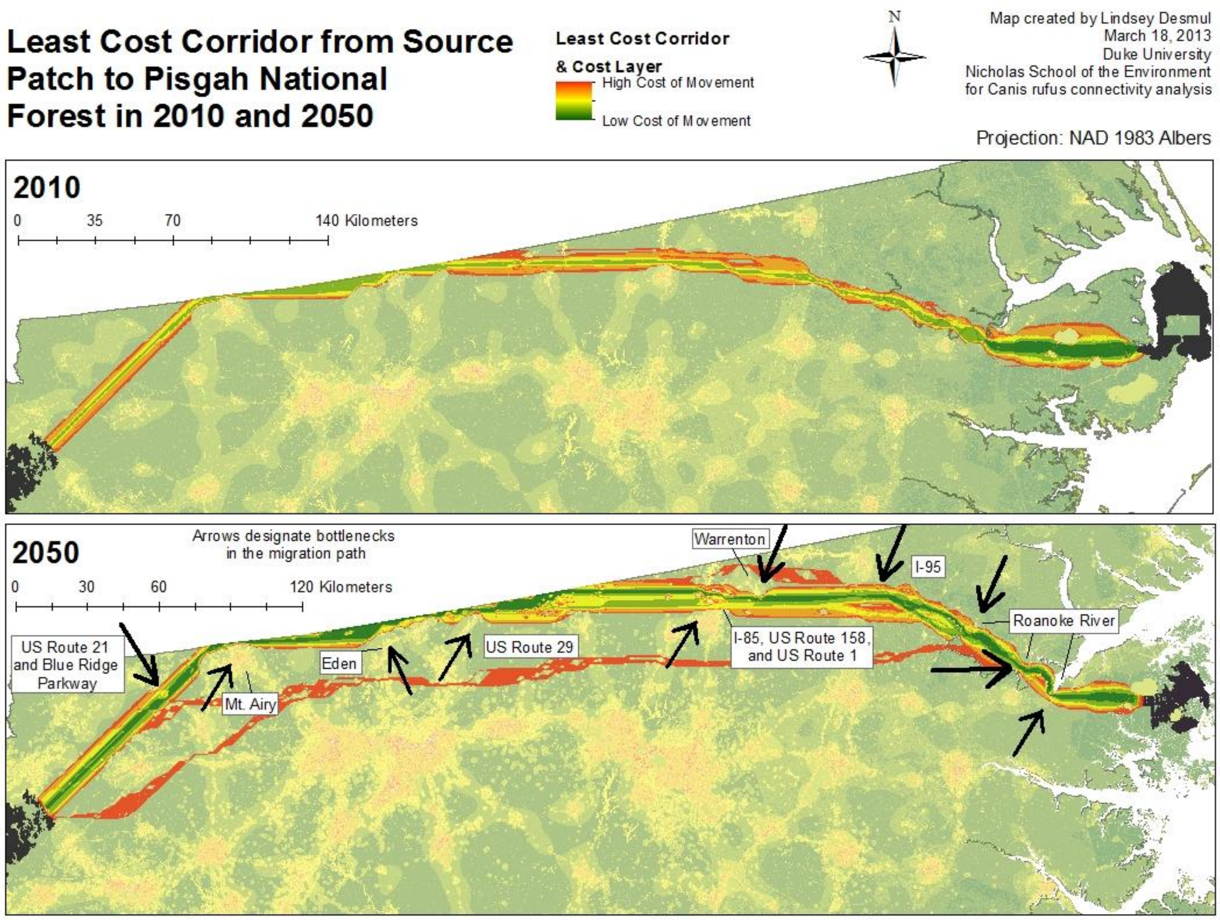

Figure 12 - Least cost corridor from source patch to Pisgah National Forest in 2010 and 2050. Barriers to migration include the towns of Mt. Airy, Eden, and Warrenton, NC, the Roanoke River, and several different highways including I-85, and US Routes 29, 158, 1, and 21.

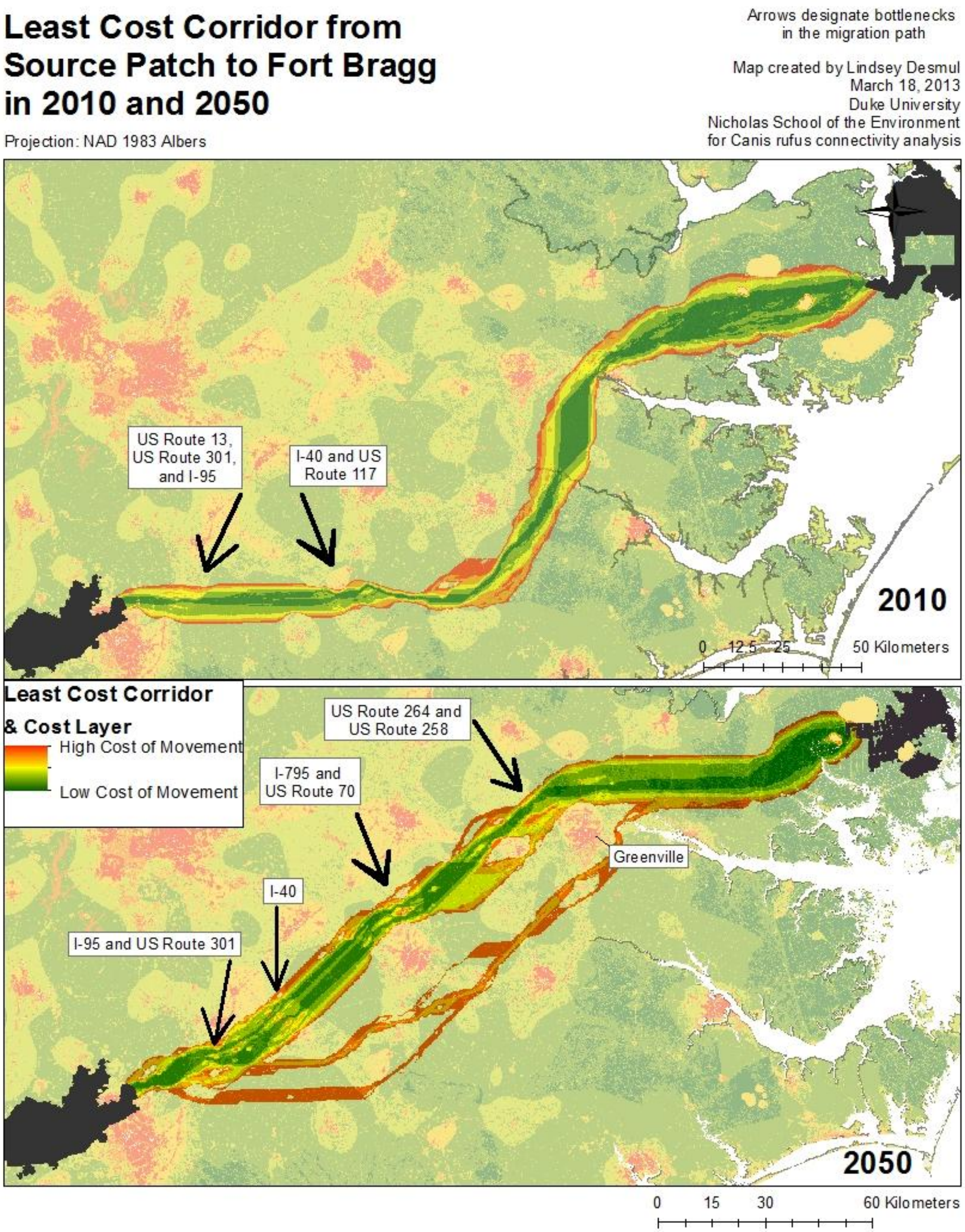

Figure 13 - Least cost corridor from source patch to Fort Bragg in 2010 and 2050. US Routes 117, 13, and 301 and Interstates 40 and 95 are barriers to migration in 2010. In 2050, barriers to migration include US Routes 264, 258, 70, and 301, as well as Interstates 795, 40, and 95. The town of Greenville, NC is also a slight barrier.

20,000 meters east of patch 7, the corridors are not dramatically different from patch 7 corridors. The main causes of barriers include Roanoke River, the intersection of US-1, US-158, and I-85, the town of Eden, and the intersection US-21 and the Blue Ridge Parkway (figure 12). These patches contain more barriers due to the extensive lengths of the corridors.

Habitat Patch Number	2010 Minimum Distance (in m) to Patches via Least Cost Path	2050 Minimum Distance (in m) to Patches via Least Cost Path	*Difference in Distance to Patch from 2010 to 2050*
17	353099.9	340583.4	-12516.4
15	374992.4	372291.1	-2701.3
9	582639.8	579974.0	-2665.8
10	653164.3	650517.5	-2646.8
30	72358.5	69739.0	-2619.5
29	56965.8	54352.0	-2613.8
7	530926.3	528322.4	-2603.8
14	443671.1	441071.8	-2599.3
34	238690.3	236094.8	-2595.5
11	493455.5	490907.4	-2548.1
12	482304.8	479757.1	-2547.7
8	557749.6	555363.6	-2385.9
3	581112.1	578731.8	-2380.3
1	622302.2	619929.2	-2373.0
4	581459.8	579243.8	-2215.9
33	249227.7	247287.3	-1940.3
5	550789.0	548933.6	-1855.4
16	338154.9	336982.8	-1172.1
18	356866.3	356325.7	-540.6
6	491979.9	491661.2	-318.8
2	637636.9	637357.8	-279.2
20	256829.8	256798.0	-31.8
19	309601.4	311430.9	1829.5
21	245147.6	248160.2	3012.7
22	233992.6	238870.6	4878.0
26	186279.1	194143.2	7864.1
23	256713.4	264967.5	8254.1
24	256909.1	267212.8	10303.7
25	247948.6	263817.7	15869.1
27	147084.3	166215.5	19131.3
28	121385.8	141382.4	19996.7
31	109036.2	NA	NA
32	86099.7	NA	NA

Table 5 - Minimum distance from source patch to each habitat patch with new values for 2050. New values had to be calculated since the source patch for 2050 is approximately 34,000 meters inland due to increased inundation, thereby creating shorter distances in 2050 than in 2010.

The corridor to Fort Bragg (patch 20) offers two completely different routes between 2010 and 2050. In 2010, the corridor takes a southerly route and then progresses west to the habitat patch, while in 2050 the corridor takes a more direct route southwest. The barriers seen in both corridors to patch 20 are largely highway related. In 2010, the wolves must pass US-13 and US-301 as well as Interstate 95 and Interstate 40. In 2050, the wolves would have to pass I-795, I-40, and I-95, which would be very risky if wildlife overpasses were not available. Other barriers include the Neuse and Tar Rivers in 2010 and Greenville, NC in 2050 (figure 13).

Distance of Travel

To determine if the wolves would have to travel a larger distance with changes in connectivity between 2010 and 2050, the length of each least cost path was calculated. However, because the source location in 2050 is not Alligator River due to inundation, the distances for 2050 are all shorter than the distances for 2010. While the two source patches are very close to one another, the starting point of connectivity for 2050 is approximately 34,000 meters inland of the starting point for 2010. If this value is added to each segment length for 2050, it appears that the selected habitat patches that are closer to the source patch in 2050 than in 2010 include patch 29 and 30 (table 5). The distance to patch 26 increases by almost 8,000 meters, patch 27 increases by 19,000 meters, and patch 28 increases by 20,000 meters. The distance to patches 7 and 11 decreases by approximately 2,500 meters, while the distance to patch 20 decreases by a mere 31.8 meters. Considering most red wolves travel up to 16,000 to 32,000 meters per day to hunt (Dybas, 2011), these distances do not seem to pose a problem for the wolves.

Discussion

Future Implications

While overall habitat connectivity from the Albemarle Peninsula may not change dramatically from 2010 to 2050, this analysis highlights some important conservation efforts necessary for future migration of the species. First, it appears that the state needs to consider constructing wildlife over- or underpasses for major interstate highways such as I-40 and I-95. This would make migration easier for the red wolf as well as other species, and it would likely reduce the amount of human injuries caused by vehicle collision. This analysis located several locations that would benefit from these under- or overpasses, but if they were placed in locations other than those discussed it will still likely benefit the species. River overpasses could also be considered for the larger deltas of the Tar River, the Roanoke River, and the Neuse River, however this may be unnecessary due to the swimming ability of wolves. More research should be done on how feasible it is for the wolves to pass such barriers, and what distances they are willing to swim to reach a new habitat, prey items, or potential mates.

Another concern stems from whether these wolves will physically be able to make the journey from one side of the state to the other. In other words, how far will the wolves actually travel before either turning back or denning in unsuitable habitat? Most wolves have a large habitat range and they have been known to travel long distances for food. As previously stated, red wolves have been known to travel up to 20 miles per day to hunt (Dybas, 2011), which could get them halfway to patches 29 and 30 in one day. Judging by this scenario, it would be surprising if wolves were not already claiming these protected areas as their habitat. If the wolves are not currently living here, or if the patches do not provide favorable habitat, they could provide cover and respite during the commute to the other selected patches.

Being habitat generalists may make distribution modeling and connectivity analyses more difficult, however this adaptation should work in the favor of red wolf survival and range expansion. If a wolf was motivated to travel across the state in search of new habitat, their lack of habitat preference will make it easier to find cover in which to rest. Traveling in this way, a red wolf could potentially make it to the mountain patches within three weeks. This kind of extensive migration is not unheard of among other large apex predators. Gray wolves in Montana tend to move an average of 113 kilometers from where they were born in their lifetime, and some are known to have dispersed up to 800 km (Montana Field Guide, 2013). The cougar (*Puma concolor*) has been known to move up to 483 km, and approximately 5 km daily (Thompson & Jenks, 2005). A close cousin to the red wolf, coyotes in eastern Washington have been known to have a habitat range of 92 km^2 (Shivik & Wilson, 2011) and transient eastern coyotes have been shown to cover up to 100.5 km in one night (Way, 2011). With over fifty percent of the wild red wolves wearing radio collars, the U.S. Fish and Wildlife Service likely has telemetry data showing how their wolves move through the landscape, but that data is not available for public consumption. It is possible that some red wolves from the peninsula have already moved to the Appalachian mountain region in search of food and habitat. Therefore, the likelihood of natural range expansion is high, as long as survival rate does not decrease and family groups can be established in the new locations.

Additional Vulnerabilities

Because connectivity is not assumed to be greatly affected in the future with the growth of urban development and sea level rise, other threats to survival need to come to the forefront of red wolf conservation in order for the species to thrive. One of the main threats currently acting as a barrier to red wolf survival is coyote interbreeding and hybridization. One of the many causes of their first extinction was increased hybridization with coyotes, reducing the amount of pure-bred wolves. The offspring of coyote-red wolf interbreeding produces a viable hybrid, which can breed and possibly displace or replace the red wolves altogether. This genetic extinction has been seen before between rare native species and more abundant introduced species, yet it is a problem commonly overlooked by wildlife managers (Rhymer and Simberloff, 1996). In this case, however, it is among the top concerns in red wolf conservation.

Prior to examining connectivity, coyote data was gathered in an attempt to model coyote population density for the state of North Carolina. The goal was to include the population density information in the connectivity and habitat suitability analysis. All coyote data was collected by the North Carolina Wildlife Resources Commission (NCWRC) and obtained for the study from Colleen Olfenbuttel, a wildlife biologist with the Commission. Collected through a voluntary Annual Trapper Harvest Survey and Fur Harvest/Dealer Reports, the data spanned the years 2003 to 2011 and was available for ninety-seven out of one hundred counties. The data was not used in the analysis due to the fact that all one hundred counties were not equally represented by the data. Also, the nature of the survey questions - asking hunters to honestly report how many kills of each species they made in the last year - may have skewed respondents' answers leading to a biased dataset. It is also likely that not all furs harvested and animals trapped and killed were registered with the NCWRC and therefore were not available in the Fur Harvest Reports. This data would likely lead to an unreliable model, therefore it was assumed that coyotes inhabit each county in North Carolina with relatively equal population densities throughout the state. This is unlikely to be the case, therefore future studies should focus on coyote detection (via radio telemetry, camera traps, hair snares, or live traps) or citizen science data (via surveys) to collect more detailed information about how coyotes are using the southeastern landscape. This information can inform wildlife managers about the locations of high coyote density in relation to where red wolves are present or will be in the future- leading to the possibility of preemptively sterilizing the coyote population before they come into contact with the wolves.

Another significant factor that could impair red wolf survival is human-wolf conflict. Since the spotlight hunting law passed in August of 2012, eight wolves have been shot and killed, which is an extremely large number for a population with only one hundred individuals. Although the law was passed to help control the coyote population in the state, in theory acting as a benefit to the red wolves, it has instead put the wolves at risk. Regardless of the law, the U.S. Fish and Wildlife Service has stated that red wolf mortality rates tend to increase during the fall hunting season, resulting in a mean mortality rate of four wolves per year over the last seven years (Friends of the Pocosin Lakes NWR, 2012). To benefit the attempt to expand red wolf population, resources should be allocated to community outreach and education programs. Many residents of North Carolina still stand firmly against the wolf introduction project, passing the prejudice to their children and perpetuating the negativity. However, this can be changed with increased education. Surveys should be distributed to determine a baseline measurement of the attitudes of residents living within the wolf's range. Once a baseline is established, the survey should be sent out on a biannual basis to determine whether attitudes are progressing, and those regions expressing distrust or disdain should be targeted for increased educational opportunities. Non-lethal deterrent methods should be taught through different media such as town meetings, informational brochures, and classroom activities for school-age children. Peaceful coexistence may never be fully obtained, but if the number of gunshot mortalities per year can be reduced it would immensely benefit the survival of the red wolf.

Study Limitations

This analysis shows that the connectivity of the landscape in which the red wolf lives is not a large concern for species survival, however the results are not entirely reliable given that predictions of future sea level rise and urban growth are limited. There is no model that gives a perfect projection of the future, especially for something as variable as development. Changes in the real estate market and the national and state economy could dramatically alter how the landscape is developed over time. Likewise, different environmental and anthropogenic factors could impact how sea level changes over time, leading to lower or higher levels of connectivity.

To address this uncertainty and refine management implications, the analysis could be run again using different projections of sea level rise.

The connectivity results also rely heavily on the cost surface analysis, which is similar to the two models in terms of the uncertainty of its accuracy. The cost surface is created from six variables, three of which are generated from models. One variable, the NLCD layer, was assigned cost values based on expert opinion. However, even red wolf biologists may not be certain about which habitat a wolf is most likely to move through. For example, the experts suggested that wetlands be given a higher cost score than forested or grass land, even though the current red wolf range consists largely of wetlands. Also, the experts may have rated certain land cover types higher in cost given the threats associated with them. The cost value given to the "pasture/hay" land cover type was higher than the cost given to forested land, largely because traveling through pastureland can induce human-wolf conflict. However, it has been proven that red wolves prefer to move through and spend time in pastures and croplands (Dybas, 2011), therefore these are likely the habitat types they would choose. The cost values for the other variables (i.e., road density and slope) were chosen somewhat arbitrarily. While they were based on expert opinion from published literature, only certain values were listed as favorable or threatening to the wolves. For example, road densities greater than 0.25 km/km^2 are known to deter wolf movement, therefore values above 0.25 were given higher cost values. However, it was assumed that mid-density values would be less costly to movement than the highest density values, therefore the values above 0.25 km/km^2 were split into two categories and given appropriate cost units. The cost surface also requires each variable to be assigned a percent influence value, with variables that greatly impact movement given a higher influence. With no expert data explicitly stating how each variable affects migration, these values were also somewhat arbitrarily chosen, and changes to these influences could alter the habitat connectivity results.

To be effective, a connectivity analysis should look at connectivity between and among known habitat patches and those areas that the species may prefer to inhabit. However, this analysis focused only on currently protected areas in the state rather than habitat that might be especially appropriate for red wolves. The habitat patches selected as the most suitable from the analysis may not actually be good habitat for the wolves as a result of undisclosed variables in those landscapes. For example, Camp Lejeune may not provide suitable habitat due to the amount of daily human activity and the noise generated by range exercises, including demolition and firearms training (MCB Camp Lejeune, 2006).

In view of the high amount of money already put into this reintroduction program and the large amount of area that the wolves need to be successful, however, it seems prudent to only consider swaths of land that are currently protected. Without the obstacle of land acquisition, all resources can be used to assure safe wolf migration and survival in their new habitat, as well as researching the preferable land types that wolves would choose to live in. The expansion of their range into these new patches will, undoubtedly, tell wolf biologists if the red wolf really is a habitat generalist.

To provide more realistic results to wildlife managers, the analysis should be expanded to also include habitat patches outside of North Carolina. Red wolves do not recognize state boundaries, therefore they could easily travel into Virginia or South Carolina from their current location. However, other states were not considered in this analysis because of the variation in state geospatial data. Until geospatial data is standardized for the entire United States, large-scale analyses will be difficult and will inevitably include some sources of error. Nevertheless, it is important to red wolf conservation to consider all possible areas of migration.

Finally, any connectivity analysis using only least cost paths or corridors will run into the question of whether or not species will actually migrate in that way across the landscape. Since the least cost path is only a single-cell wide line, there is almost zero probability that the wolf will follow this movement pattern. The wolves are more likely to follow the corridor since it shows a wider distribution of possible movement, however it is still limited in its usefulness due to the fact that the wolves would have to leave and enter each patch at one certain point, which is improbable. A more in-depth analysis may be completed by using the program

Circuitscape, which uses electrical circuit theory to calculate patterns of movement in heterogeneous landscapes through conductance, voltage, and current throws. This gives a more realistic view of the way wildlife would randomly walk through a landscape rather than following a specific path or corridor of least cost movement by considering all possible pathways through the landscape simultaneously (McRae et al., 2008). This analysis is currently being run for the red wolf, using the entire southeastern United States as the study area, through a project funded by the South Atlantic Landscape Conservation Cooperative. Results should be available by summer 2013.

Conclusion

With a rapidly changing landscape and an ever growing human and coyote population, the future is unknown for the red wolf. Whether they will survive depends largely on their ability to expand their population range and travel amongst various threats and barriers safely. As the primary threat to the species, humans can help to mitigate some of these barriers in small ways from adding infrastructure to aid in safe travel over roadways to improving the public perception of carnivore coexistence.

Now that the coyote has replaced the red wolf and filled the carnivore niche that was left empty half a century ago, some may wonder what purpose the wolves now serve in the ecosystem. Why is it so important that this species escapes extinction once again? Aside from restoring natural ecosystem function by culling the large deer and feral hog populations, some people believe humans have an essential responsibility to act as stewards to the land, saving a species with intrinsic value such as the wolf. Regardless of whether saving the red wolf is an ethical or scientific debate, the species has survived an incredibly difficult past against all odds. The future may hold uncertainties for the species, but the red wolf will continue to be an important ambassador for wildlife and carnivore conservation for years to come.

References

Alion Science and Technology. (2009). "Impacts from Sea Level Rise in the Albemarle-Pamlico Region: Dare County Peninsula." Albemarle-Pamlico National Estuary Partnership's Science & Technical Advisory Committee meeting. 29 April 2009. Accessed February 20, 2013. http://portal.ncdenr.org/c/document_library/get_file?uuid=61a24806-fc1e-4b3e-bea1-0a7141bdfd0e&groupId=61563

Bamber, J.L. and Aspinall, W.P. (2013). "An expert judgement assessment of future sea level rise from the ice sheets." *Nature Climate Change*. January 6, 2013. doi:10.1038/nclimate1778.

Callaghan, C., Paquet, P.C. and Wierzchowski J. (1999). "Highway effects on Gray Wolves within the Golden Canyon, British Columbia." ICOWET III, The International Conference on Wildlife Ecology and Transportation, Missoula, USA.

Chadwick, J., Fazio, B., and Karlin, M. (2010). "Effectiveness of GPS-Based Telemetry to Determine Temporal Changes in Habitat use and Home-Range Sizes of Red Wolves." *Southeastern Naturalist*, Vol. 9, No. 2. Pp. 303-316.

Côté, S.D., Rooney, T.P., Tremblay, J.-P., Dussault C. and Waller D.M. (2004). " Ecological Impacts of Deer Overabundance." *Annual Review of Ecology, Evolution, and Systematics*. Vol. 35, (2004), pp. 113-147

Darnell, C. (2008). "Enhancing the Resilience of Coastal Wetlands in the Albemarle-Pamlico Region of North Carolina." *National Wetlands Newsletter*, Vol. 30 No. 6. Pp. 12-13

Dybas, C.L. (2011). "Red Wolf's Last Stand." *Natural History Magazine*. Online. Retrieved on March 9, 2013. http://www.naturalhistorymag.com/features/282268/red-wolfs-last-stand

Epperly, S.P. and North Carolina Division of Marine Fisheries. (1984). "Fishes of the Pamlico-Albemarle Peninsula, N.C. : area utilization and potential impacts." North Carolina Department of Natural Resources and Community Development - Division of Marine Fisheries. Special Scientific Report No. 42. CEIP Report No. 23. 1984.

Estes, J.A., Terborgh, J., Brashares, J.S., Power, M.E., Berger, J., Bond, W.J., Carpenter, S.R., Essington, T.E., Holt, R.D., Jackson, J.B.C., Marquis, R.J., Oksanen, L., Oksanen, T., Paine, R.T., Pikitch, E.K., Ripple, W.J., Sardin, S.A., Scheffer, M., Schoener, T.W., Shurin, J.B., Sinclair, A.R.E., Soule, M.E., Virtanen, R., Wardle, D.A. (2011). "Trophic downgrading of planet earth." *Science*. Vol. 333, No. 6040. Pp. 301-306.

Fazio, B.B. (2007). “Red Wolf (*Canis rufus*) 5-Year Status Review: Summary and Evaluation.” U.S. Fish and Wildlife Service, Manteo, North Carolina, USA. Retrieved on March 30, 2012. http://www.fws.gov/redwolf/Images/RedWolf-5YrR.pdf

Friends of the Pocosin Lakes NWR. (2013). "Red wolves endangered by rule designed to protect them - 7th wolf killed." Retrieved March 20, 2013. http://www.pocosinlakesfriends.org/?page=news&nid=2427&do=s&PAGENUM_GET=1

GlobalSecurity. (2011). "Military: Fort Bragg." Retrieved on April 15, 2013. http://www.globalsecurity.org/military/facility/fort-bragg.htm

Gregg, R.M. (2010). "Alligator River National Wildlife Refuge/Albemarle-Pamlico Peninsula Climate Adaptation Project [Case study on a project of The Nature Conservancy - Nags Head Woods and the U.S. Fish and Wildlife Service - North Carolina]." Product of EcoAdapt's State of Adaptation Program. Retrieved from CAKE: http://www.cakex.org/case-studies/682 (Last updated August 2011)

Hammer, R.B. and Radeloff, V.C. (2005). Housing density model by decade, 1940-2030. Funded by the USDA Forest Service North Central Research Station. University of Wisconsin - Madison.

Hinton, J. W., and Chamberlain, M. J. (2010). “Space and habitat use by a red wolf pack and their pups during pup-rearing.” *Journal of Wildlife Management*, 74(1), 55-58. Retrieved on March 30, 2012. http://search.proquest.com/docview/234108418?accountid=10598

Holland, J.S. (2004). "The Wolf Effect." National Geographic Online. Retrieved on April 15, 2013. http://ngm.nationalgeographic.com/ngm/0410/resources_geo.html

Karlin, M.L. (2011). "The Endangered Red Wolf (*Canis rufus*): Spatial Ecology of a Critically Imperiled Species in a Human-Dominated Landscape". Dissertation for The University of North Carolina at Charlotte.

MCB Camp Lejeune. (2006). "Pre Final 2006 Integrated Natural Resource Management Plan (INRMP) May 2006." Environmental Management Division Installations & Environment Department Report. Retrieved on March 20, 2013. http://www.lejeune.usmc.mil/emd/INRMP/INRMP.htm

McRae, B.H., Dickson, B.G., Keitt, T.H., and Shah, V.B. (2008). "Using circuit theory to model connectivity in ecology, evolution, and conservation." *Ecology*, 89(10). Pp. 2712 - 2724.

McVey, J.M. (2012). "Assessing Food Habits of Red Wolves (Canis rufus) and Coyotes (Canis latrans) in Eastern North Carolina". Master's thesis, North Carolina State University. (Under the direction of Dr. Christopher E. Moorman and Dr. David T. Cobb).

Microsoft Office Excel (Part of Microsoft Office Standard Edition) [computer program]. Microsoft; 2007.

Montana Field Guide. (2013). " Gray Wolf — Canis lupus. " Montana Natural Heritage Program and Montana Fish, Wildlife and Parks. Retrieved on March 16, 2013, from http://FieldGuide.mt.gov/detail_AMAJA01030.aspx

Phillips, M.K., Henry, V.G., and Kelly, B.T. (2003). “Restoration of the Red Wolf.” *Wolves: Behavior, Ecology, and Conservation*. Pp. 272-288. University of Chicago Press, 2003. Retrieved on April 1, 2012. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1228&context=icwdm_usdanwrc

Poulter, B. and Halpin, P.N. (2007). "Raster modelling of coastal flooding from sea-level rise." *International Journal of Geographical Information Science*, 22: 2, Pp. 167-182.

Rahmstorf, S. (2007). "A semi-empirical approach to projecting future sea-level rise." *Science* 315, Pp. 368-370.

Red Wolf Coalition. (2008). "The Value of Red Wolf Conservation." Retrieved April 15, 2013. http://www.fws.gov/redwolf/archives/redwolfvalue.pdf

Red Wolf Coalition. (2013). "About Red Wolves - Human Role." Retrieved March 10, 2013. http://redwolves.com/rwc/about_wolves/human_role.html

Rhymer, J.M. and Simberloff, D. (1996). "Extinction by hybridization and introgression." *Annual Review of Ecology and Systematics*, Vol. 27. Pp. 83-109.

Science Letter. (2011) "Wild hogs: Researchers examine impact of feral pigs in eastern N.C." 10 May 2011: 33. General OneFile. Web. 12 Mar. 2013.

Shivik, J.A., and R.R. Wilson. "Contender pressure versus resource dispersion as predictors of territory size of coyotes (Canis latrans)." *Canadian Journal of Zoology*. 89.10 (2011): 960+. General OneFile. Retrieved March 16, 2013.

Smith, D.W., Peterson, R.O., and Houston, D.B. (2003). "Yellowstone after Wolves." *Bioscience*, Vol. 53, No. 4. Pp. 330-340.

Sutherland, R. (2013, March 5). Personal Interview.

Terando, A., Costanza, J. and Belyea, C. Unpublished Data. Collaboration with North Carolina State University's Biodiversity and Spatial Information Center and the Department of Interior Southeast Climate Science Center.

Thompson, D.J. and Jenks, J.A. (2005). "Long-Distance Dispersal by a Subadult Male Cougar from the Black Hills, South Dakota." *The Journal of Wildlife Management*. Vol. 69 No. 2. Pp. 818-820. Article available at http://www.jstor.org/stable/3803754.

U.S. Fish and Wildlife Service. (1997). "U.S. Fish and Wildlife Service Endangered Red Wolves." October 1997. Retrieved on March 8, 2013. http://library.fws.gov/pubs4/endangered_red_wolves.pdf

U.S. Fish and Wildlife Service. (1999). "U.S. Fish and Wildlife Service Red Wolf News." July through September 1999. Volume 1 Issue 3. Retrieved on March 8, 2013. http://www.fws.gov/redwolf/archives/rwnews1-3.pdf

U.S. Fish and Wildlife Service. (2004). "U.S. Fish and Wildlife Service Red Wolf News." Summer, 2004. Vol. 5 Issue 2. Retrieved on March 8, 2013. http://www.fws.gov/redwolf/archives/04%20summer%20rw%20news.pdf

U.S. Fish and Wildlife Service. (2006). "Endangered Red Wolves." Red Wolf Recovery Program Brochure. Retrieved on April 1, 2013. http://www.fws.gov/southeast/pubs/alwolf.pdf

U.S. Fish and Wildlife Service. (2010). "Red Wolf Recovery Program 1st Quarter Report October – December 2010." Retrieved on April 1, 2013. http://www.fws.gov/redwolf/Images/20110121_RedWolf_QtrReport_FY11-01.pdf

U.S. Fish and Wildlife Service. (2012). "Red Wolf Recovery Program 1st Quarter Report October - December 2012." Retrieved on January 3, 2013. http://www.fws.gov/redwolf/Images/20130110_RedWolf_QtrReport_FY13-01.pdf

U.S. Fish and Wildlife Service. (2013). "Alligator River National Wildlife Refuge." Retrieved March 1, 2013. http://www.fws.gov/alligatorriver/

U.S. Fish and Wildlife Service. (2013). "Causes of mortality in wild red wolves (*Canis rufus*) 2010-2013." Retrieved on March 1, 2013. http://www.fws.gov/redwolf/Images/MortalityTable.pdf

U.S. Fish and Wildlife Service. (2013). "Red Wolf Recovery Program 2nd Quarter Report January - March 2013." Retrieved on April 15, 2013. http://www.fws.gov/redwolf/Images/20130416_RedWolf_QtrReport_FY13-02.pdf

Vaughan, M.R. and Kelly, M.J. (2011). "Evaluating potential effects of widening US 64 on red wolves in Washington, Tyrrell, and Dare Counties, North Carolina." Final Report. VT-NCDOT Contract No. 09-0776-10. 55pp.

Way, Jonathan G. (2011) "Eastern Coyote/Coywolf (Canis latrans x lycaon) Movement Patterns: Lessons Learned in Urbanized Ecosystems." *Cities and the Environment (CATE)*. Vol. 4: Iss. 1, Article 2. Available at: http://digitalcommons.lmu.edu/cate/vol4/iss1/2

Wheeler, T.B. (1998). "Effort to Return Red Wolves to Great Smoky Mountains Ends in Failure." Los Angeles Times online. Accessed March 1, 2013. http://articles.latimes.com/1998/dec/13/news/mn-53449

Wild South. (2012). "If you choose to dislike coyotes, know the real reasons why." Accessed March 5, 2013. http://www.wildsouth.org/images/Wildlife/coyote%20myths3.pdf

Data Sources

ESRI (Environmental Systems Resource Institute). 2012. ArcGIS Desktop 10.1. ESRI, Redlands, California.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011). "Completion of the 2006 National Land Cover Database for the Conterminous United States." PE&RS, Vol. 77(9):858-864.

Hammer, R.B. and Radeloff, V.C. (2005). Housing density model by decade, 1940-2030. Funded by the USDA Forest Service North Central Research Station. University of Wisconsin - Madison.

McKerrow, A.J., Williams, S.G., and Collazo, J.A. 2006. The North Carolina Gap Analysis Project: Final Report. North Carolina Cooperative Fish and Wildlife Research Unit, North Carolina State University, Raleigh, North Carolina. xiv + 110 pp. + appendices.

North Carolina Department of Transportation. (2012). County Boundaries with Shoreline Data.

North Carolina Department of Transportation. (2013). Statewide Primary and Secondary Road Routes Data.

Pearsall, S. (2011). Sea Level Rise Model. Funded by The Nature Conservancy. Data distributed by Analie R. Barnett.

Terando, A., Costanza, J. and Belyea, C. Unpublished Data. Collaboration with North Carolina State University's Biodiversity and Spatial Information Center and the Department of Interior Southeast Climate Science Center.

US Department of Commerce, US Census Bureau, Geography Division. (2010). 2010 Census Tracts Data.

US Geological Survey, Gap Analysis Program (GAP). November 2012. Protected Areas Database of the United States (PADUS), version 1.3 Combined Feature Class.

US Geological Survey, National Hydrography Dataset. (2012). National Elevation Dataset.

US Geological Survey, National Hydrography Dataset. (2012). NHD Flowline Data.

Appendix A

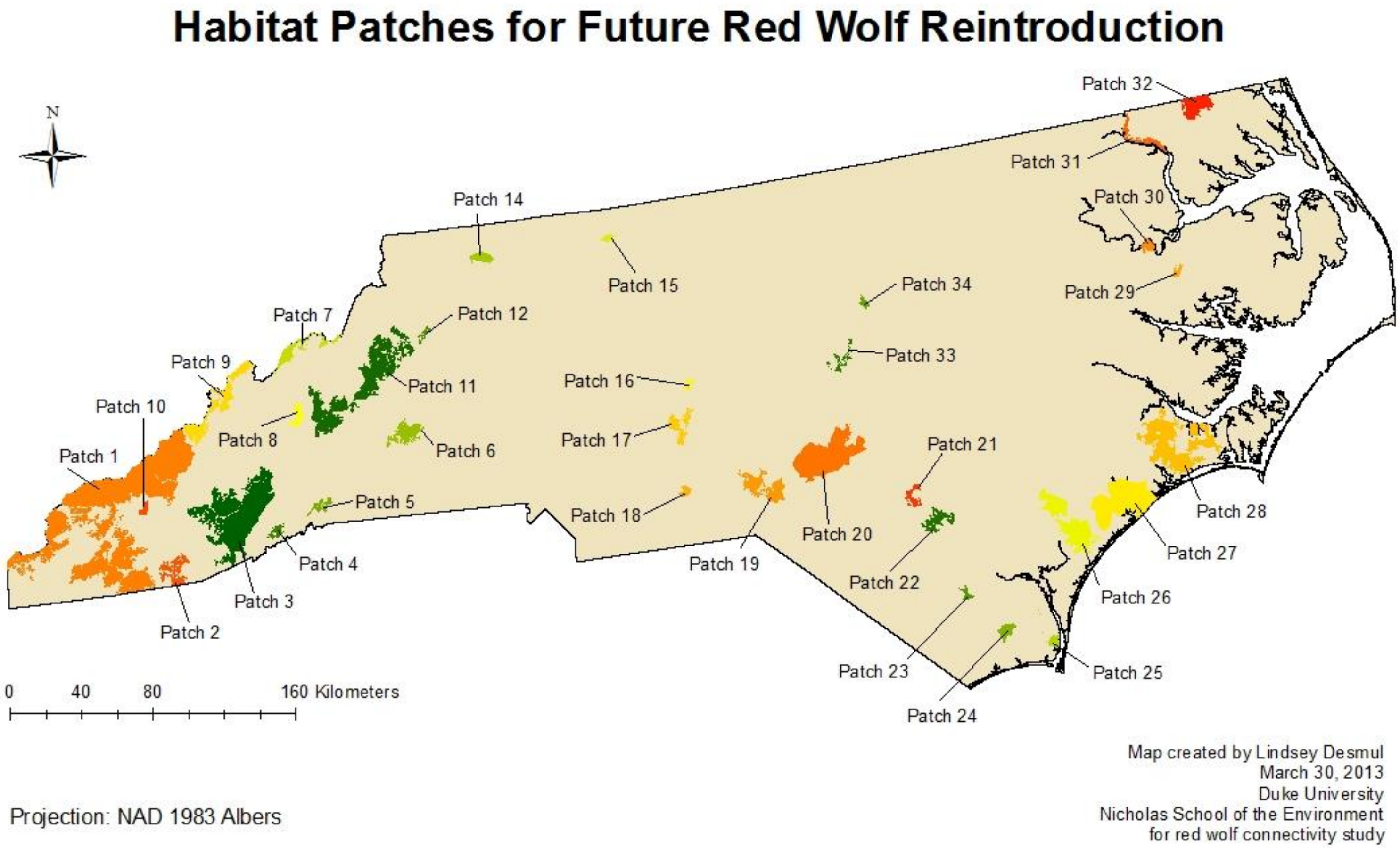

Figure A1 - Habitat patches representing future reintroduction sites for the red wolf, identified by the patch ID number used in the analysis. Some patches are large, for example patch 1, however all areas of the same color belong to the same patch.

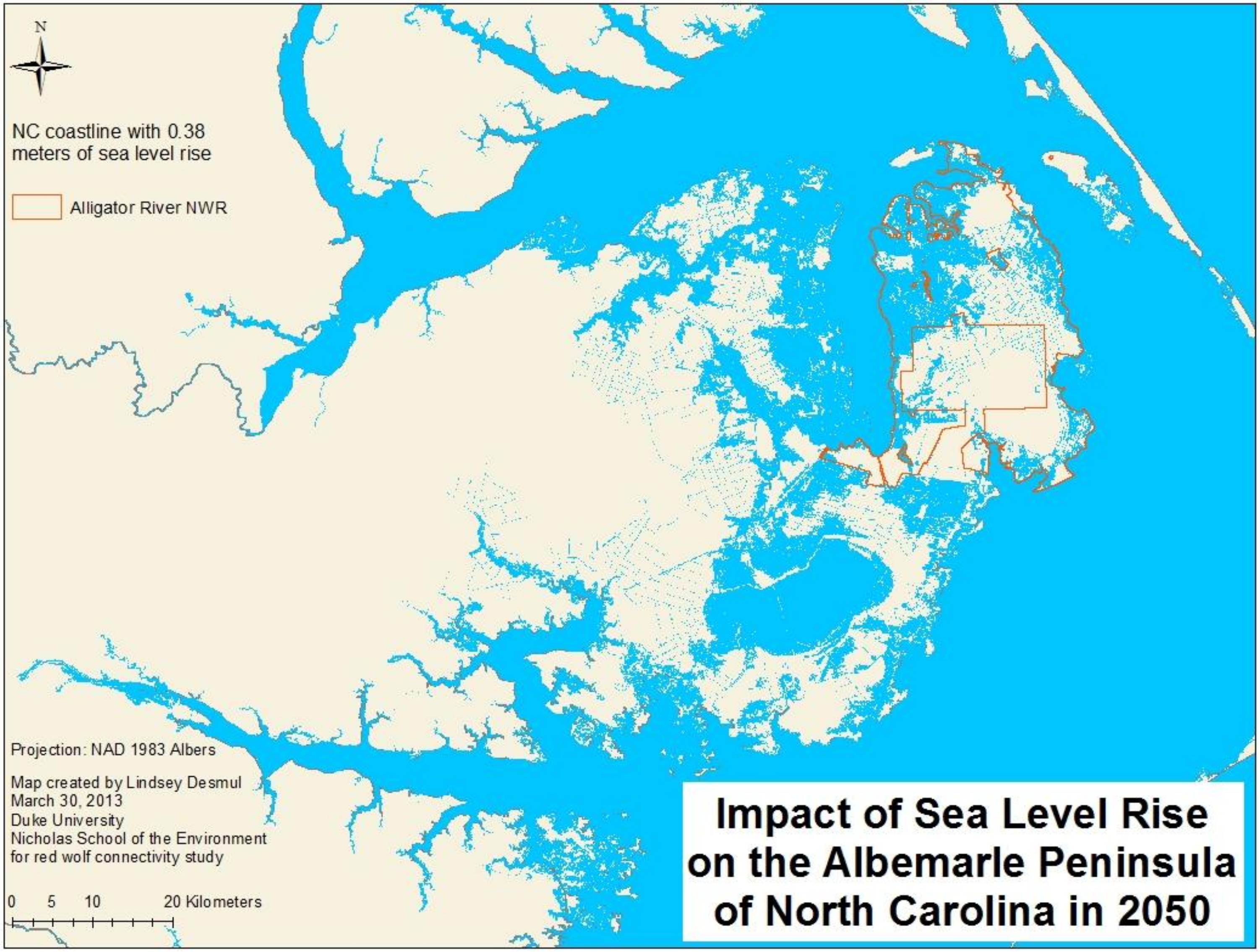

Figure A2 - Zoom-in on the Albemarle Peninsula and the impact of sea level rise inundation in the year 2050. The orange outline represents Alligator River National Wildlife Refuge, which is where a large portion of red wolves currently live. This inundation will make migration difficult in the future for wolves, establishing the importance of current range expansion.

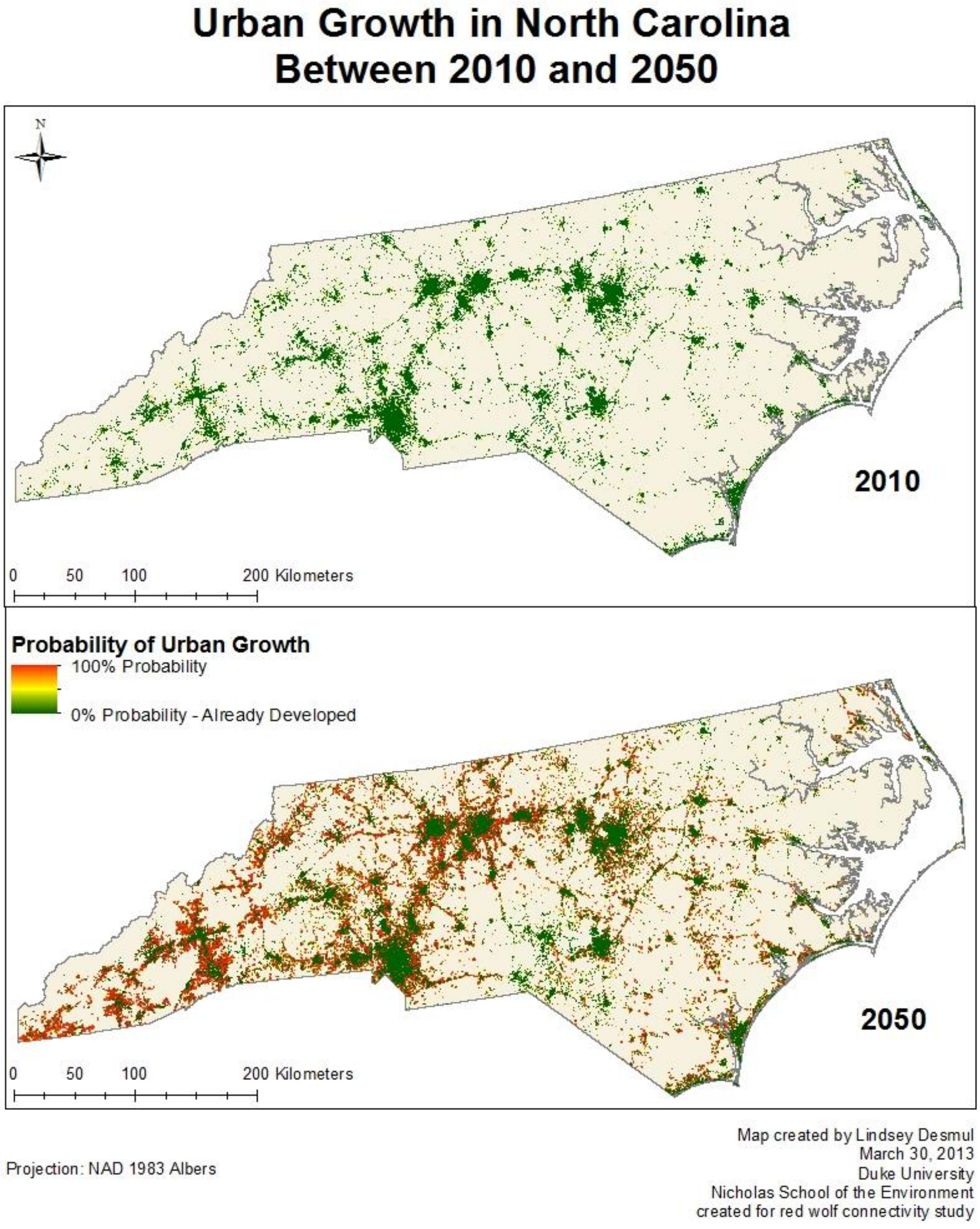

Figure A3 - Urban growth layers for 2010 and 2050 derived from Terando et al. used in the cost surface analysis. The large amount of red areas in 2050 designates increased urban development in the future, adding to urban sprawl and development centered around major highways.

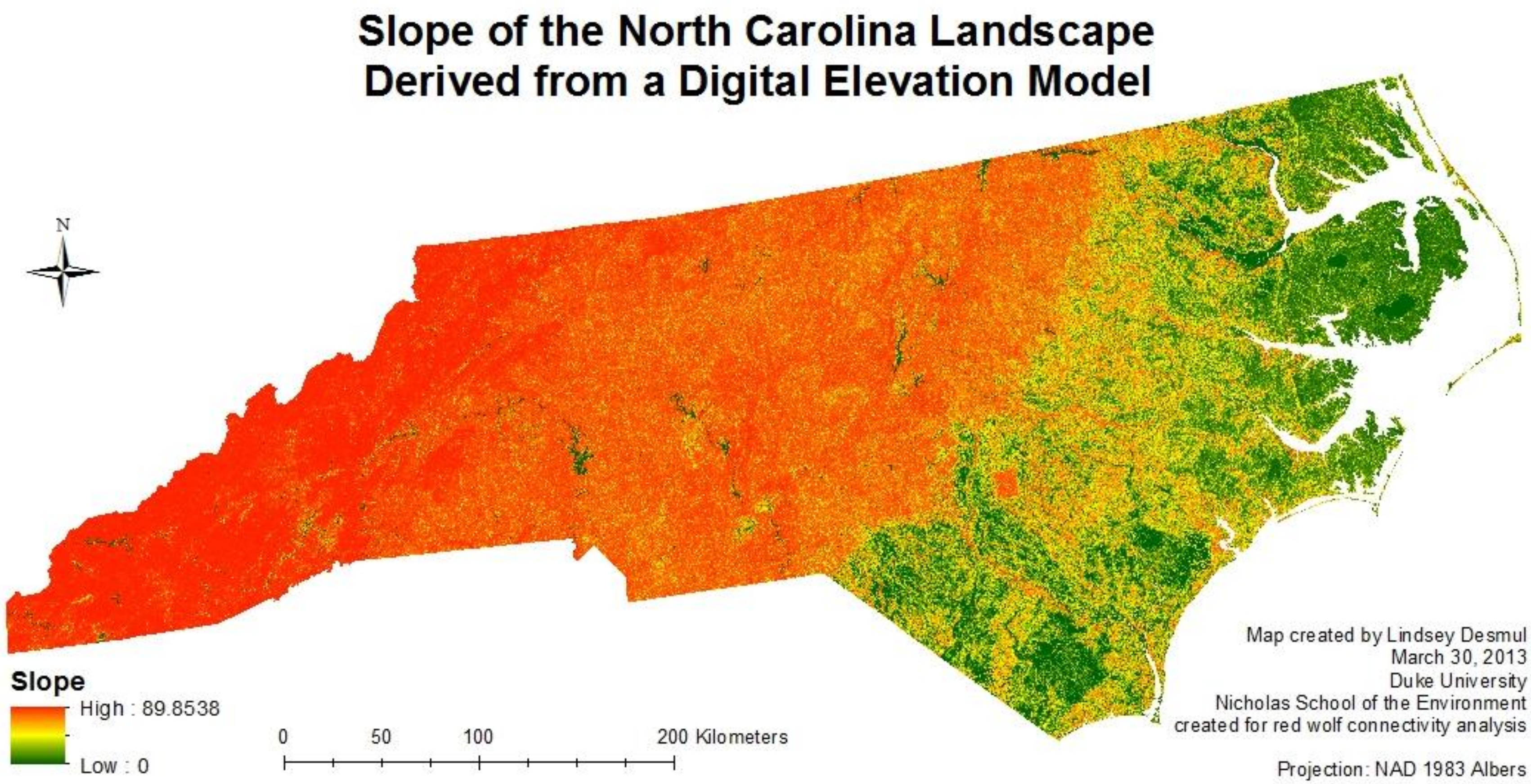

Figure A4 - Slope layer derived from a digital elevation model used in the 2010 and 2050 cost surface analysis. Areas in red have a steeper slope than those in green.

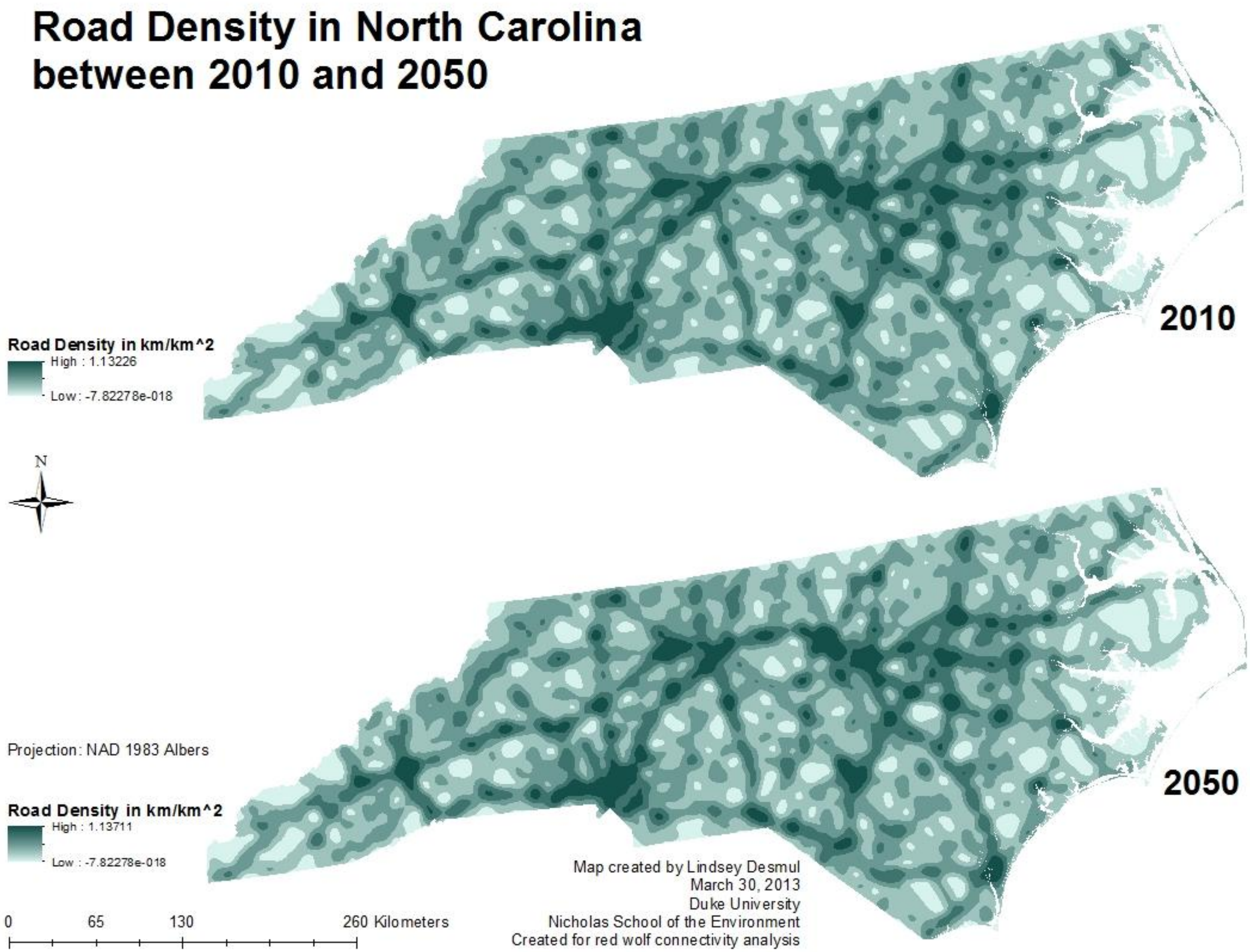

Figure A5 - Road density layers used for the 2010 and 2050 cost surface analysis. Roads used in these density layers included US and State Routes, Interstates, and Federal Highways. Projected highways were also included in the layer used in the 2050 analysis.

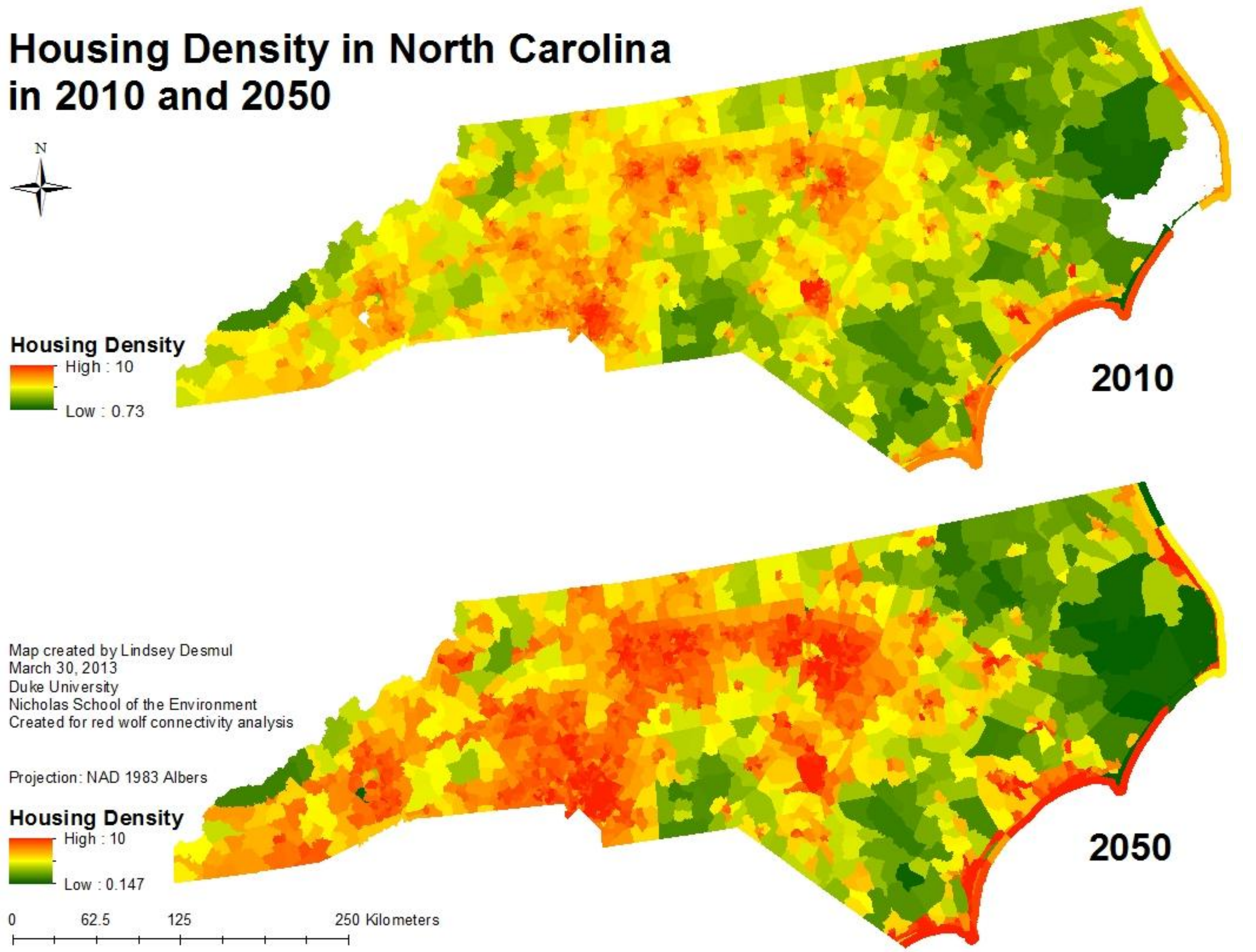

Figure A6 - Housing density layers derived from a housing density model created by Hammer and Radeloff (2005). The 2010 layer was created by Hammer and Radeloff, while the 2050 layer was extrapolated from the other data layers.

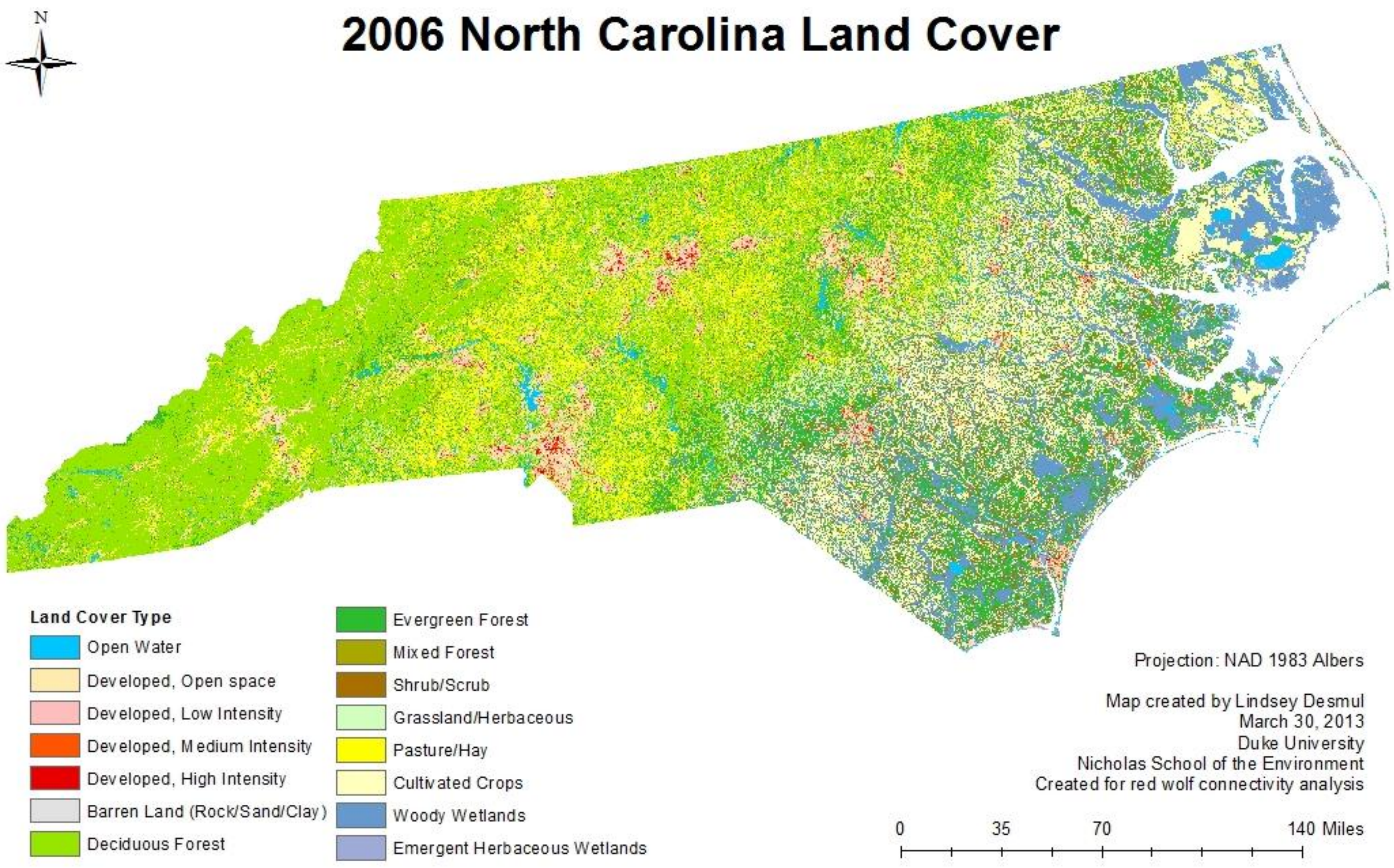

Figure A7 - National Land Cover Dataset from 2006, which was used as a constant data layer from 2010 to 2050. This data layer was created by USGS, and shows the different land cover types throughout North Carolina. Land cover plays a very important role in determining how wildlife moves throughout the landscape, therefore it is important to consider in a connectivity analysis.

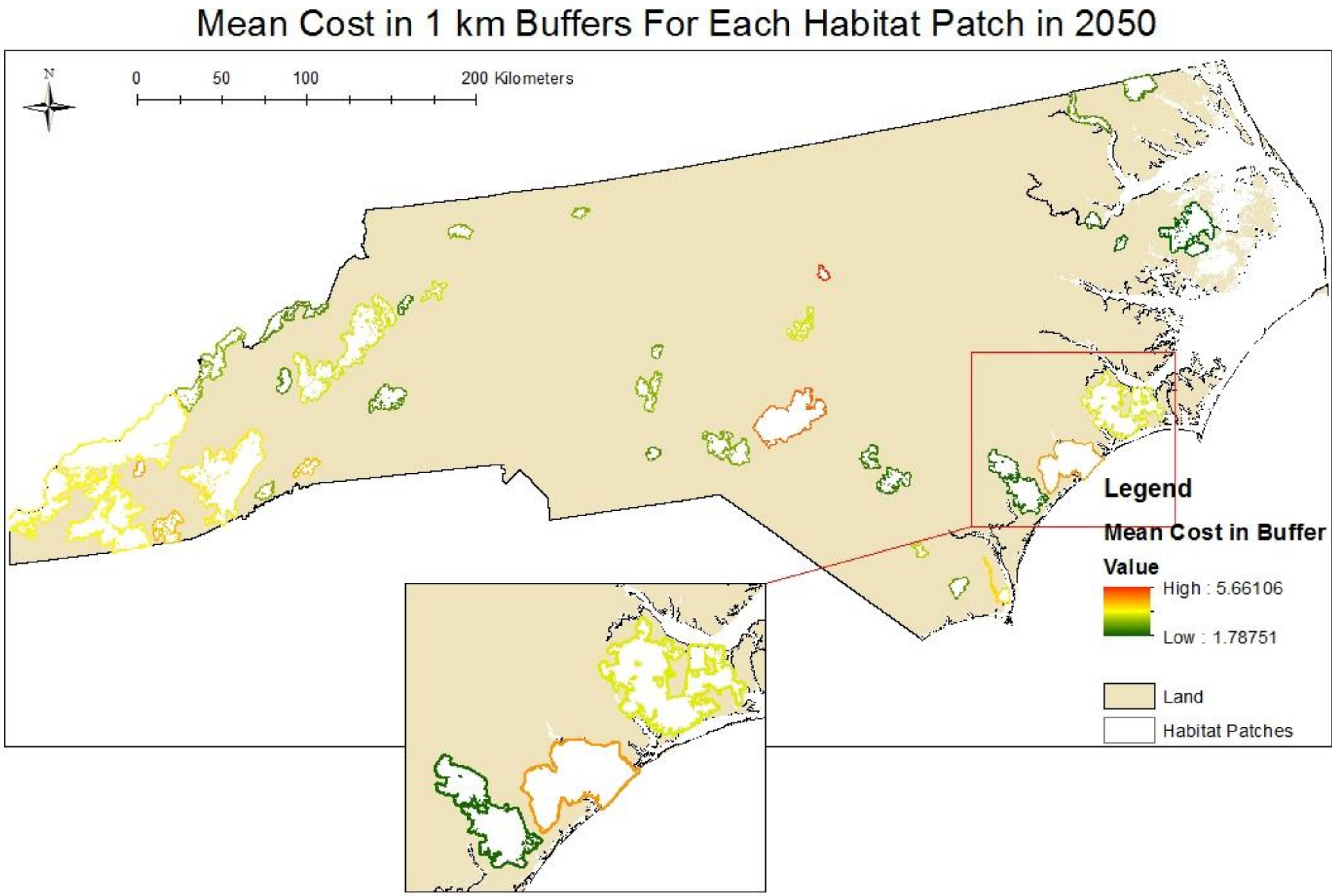

Figure A8 - Each patch was buffered 1 km and the mean amount of cost in that buffer was calculated. The color scheme shows the mean cost score of each patch buffer, with red designating a high mean cost and green designating a low mean cost. For this analysis it was assumed that red wolves would avoid habitat patches that are surrounded by high cost.

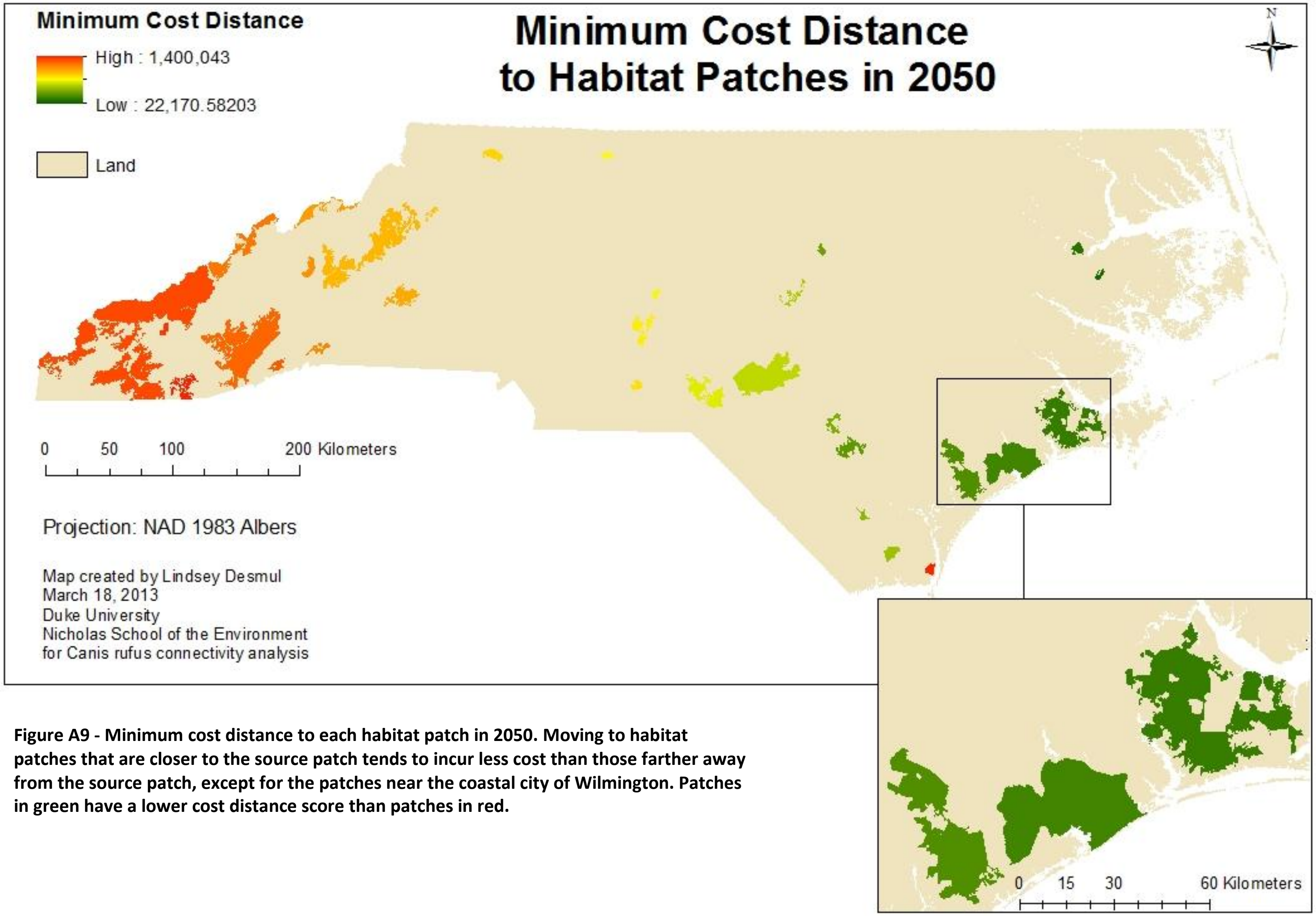

Figure A9 - Minimum cost distance to each habitat patch in 2050. Moving to habitat patches that are closer to the source patch tends to incur less cost than those farther away from the source patch, except for the patches near the coastal city of Wilmington. Patches in green have a lower cost distance score than patches in red.

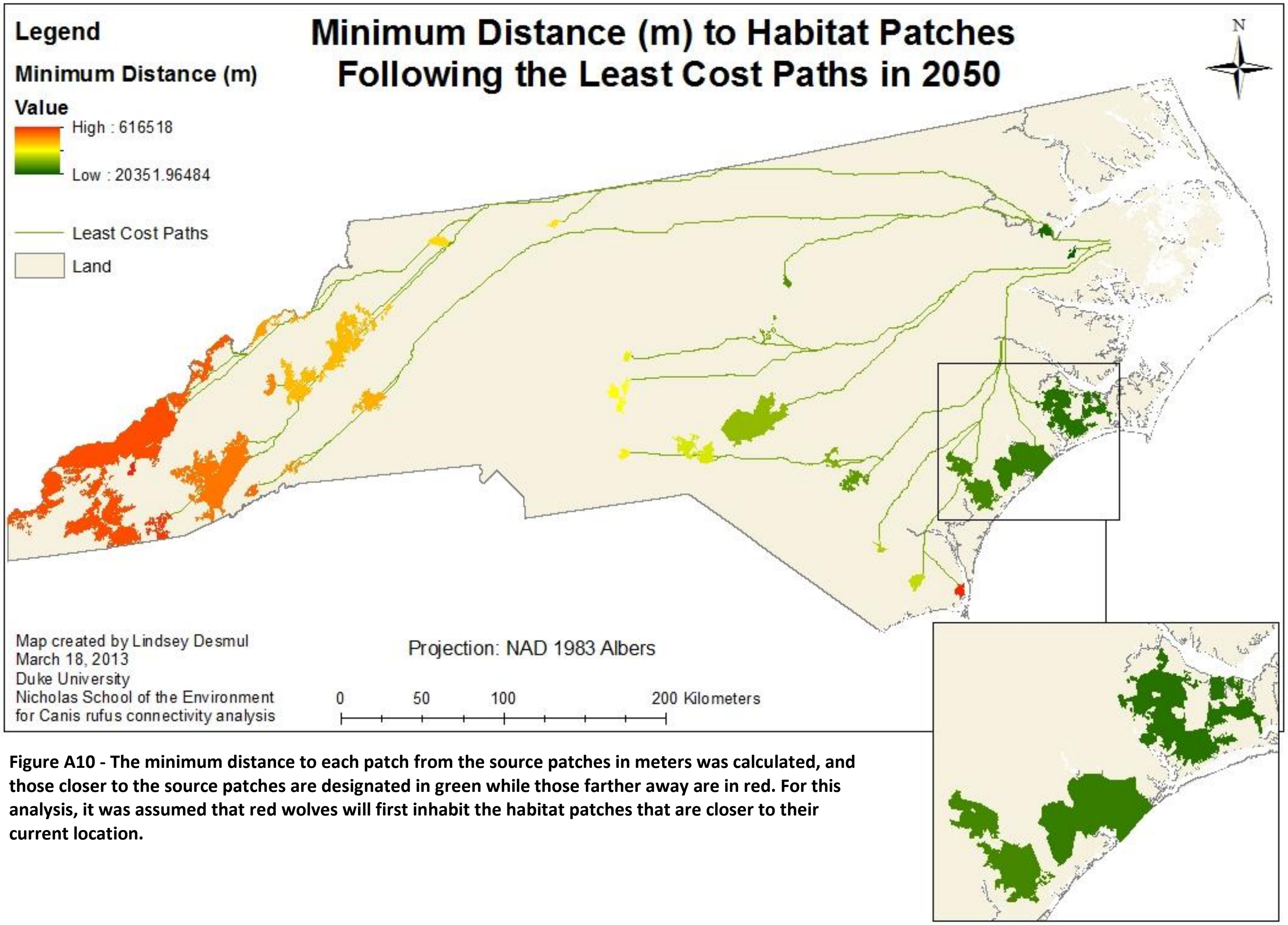

Figure A10 - The minimum distance to each patch from the source patches in meters was calculated, and those closer to the source patches are designated in green while those farther away are in red. For this analysis, it was assumed that red wolves will first inhabit the habitat patches that are closer to their current location.

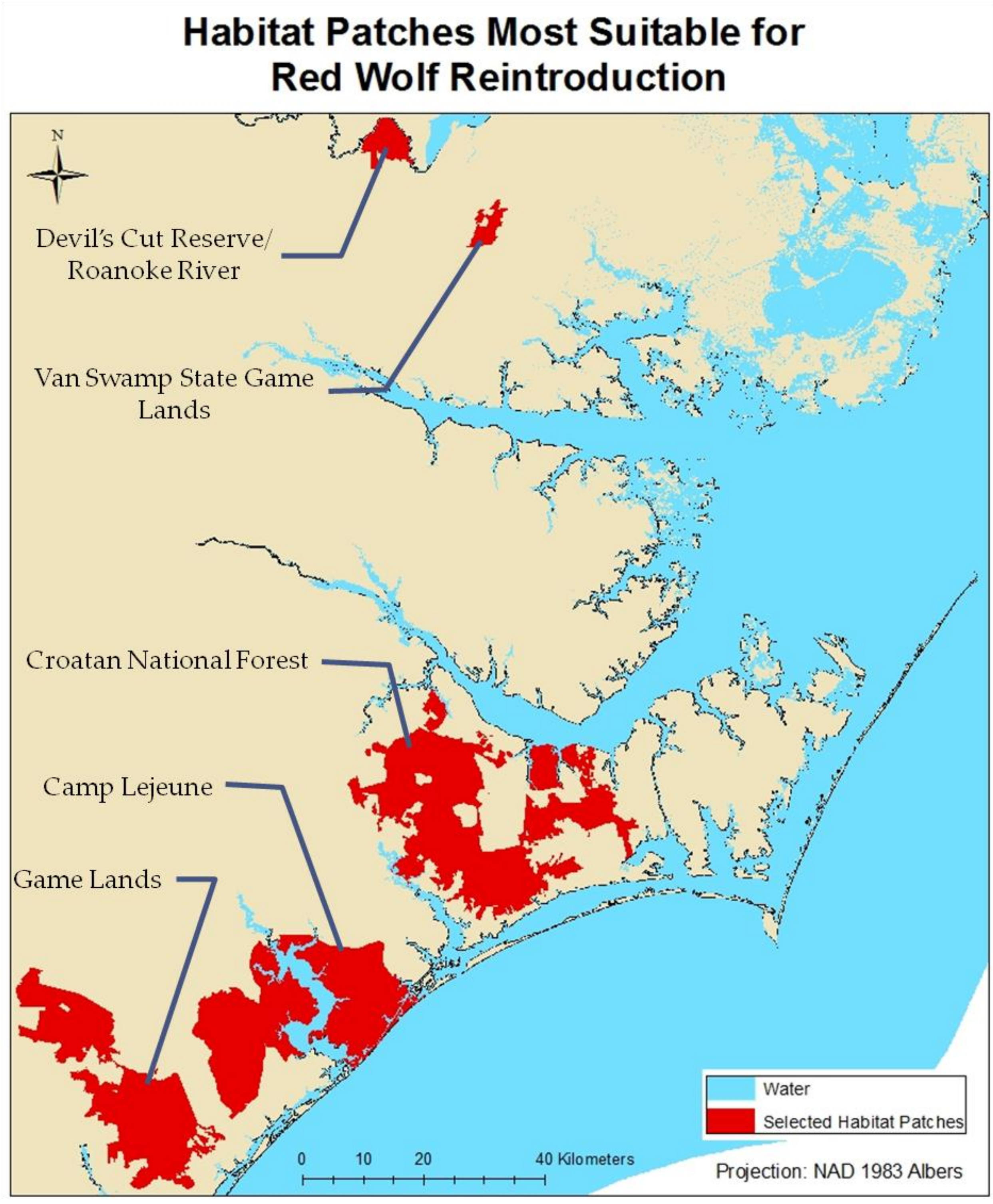

Figure A11 - Five habitat patches were selected as ideal for natural red wolf reintroduction by 2050. These patches are highlighted here and are identified by the name of the protected areas that make up the habitat patch.