PRIORITIZING CONSERVATION AREAS FOR LONGLEAF PINE FORESTS IN NORTH CAROLINA:

A spatial analysis of 3 major threats (fire suppression, urbanization, and climate change)

By

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Executive Summary

Longleaf pine forest once dominated much of the landscape in the southeastern United States, but its distribution has been diminished to approximately 3% of its historical range. As a fire-dependent ecosystem, it is now widely accepted that prescribed burning is a necessary tool in longleaf pine management and restoration. In North Carolina, longleaf pine (LLP) forests currently managed with fire are concentrated in protected natural areas that tend to coincide with designated habitat for the Red-cockaded Woodpecker, one of many federally endangered species dependent on LLP forests. While single-species management has proven highly successful for endangered species, conservation of broad ecosystems like longleaf pine may require additional pieces for prioritizing management actions.

This project provides a spatial assessment of current conditions and future projections for three major threats to longleaf pine forests: fire management changes, urbanization, and climate change. I use land cover data to extract the land cover classes containing longleaf pine in North Carolina. Due to the strong link between recovery of the Red-cockaded Woodpecker (RCW) population and restoration of the longleaf pine ecosystem, I use RCW habitat requirements as a proxy to isolate good quality longleaf pine habitat patches in North Carolina that are outside designated protected area boundaries. These patches are used as the study area.

In this analysis, I first use the unprotected longleaf pine patches to identify areas not currently managed with prescribed fire and thus are inherently at risk. To demonstrate the current deviation from the natural fire regime, I illustrate the spatial distribution of historical fire regimes within the study area patches for comparison. In the second part of my analysis, I use urban growth projection data to isolate patches that are likely to be highly threatened by urbanization in the coming decades based on their proximity to current and future development. In the third analysis section, I classify the patches by relative importance value and resilience to changing climatic conditions. Finally, I synthesize these analyses yielding a map of the total potential threat posed to the unprotected longleaf pine patches given the current and future trends of these combined threats.

Application of foraging habitat requirements for the Red-cockaded Woodpecker to the current distribution of unprotected longleaf pine patches in North Carolina identified 2,354 longleaf pine (LLP) study patches with a combined total area of approximately 697,767 acres. The combined total area of unprotected longleaf pine patches that are currently managed with regularly administered burns is only about 8.8% of the total area of the unprotected LLP patches. Urbanization projection data shows rapid urban growth to occur in North Carolina during this century. Results from the urban growth threat analysis indicate that almost twice as many longleaf pine patches will be threatened by urban sprawl in 2100 than in 2010. Overall, the climate change impact and resilience analysis shows that changing climate is likely to have a neutral or possibly positive impact on longleaf pine patches in the coming decades. Results from the climate resilience analysis identify 623 LLP patches with high climate resilience and 409 patches with low climate resilience.

To synthesize the results from these analyses, I compare relative patch counts, area, and spatial distribution in three final threat maps: lack of prescribed fire, urban encroachment, and low climate resilience. As a single threat, lack of prescribed fire shows by far the greatest number of at-risk LLP patches. If lack of fire, urban encroachment, and low climate resilience are combined and weighted equally, 178 patches are identified as at-risk from all three threats. However, looking at only the combined threats of lack of fire and urban encroachment identifies a total of 1,168 patches covering 55% of the North Carolina longleaf pine ecosystem.

My results from these three threat analyses demonstrate that fire suppression and urbanization pose substantial risk to the unprotected longleaf pine areas in North Carolina, while climate change is likely to have little to no negative impacts on these patches. As a naturally resilient ecosystem, longleaf pine has increasing importance in regional conservation. With hundreds of thousands of acres of unprotected longleaf pine forest not currently managed with fire and at high risk from urban encroachment, targeting these patches for future management prioritization could considerably expand the extent of successfully managed longleaf pine forests in North Carolina.

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Introduction

Longleaf pine forest is a native ecosystem to the Southeastern United States. While it once was a dominant ecosystem across the region's landscape, longleaf pine distribution has been diminished to approximately 3% of its historic range (Diop *et al.* 2009). Deforestation and habitat fragmentation have resulted from the expansion of the timber industry and urbanization in the Southeast, and fire suppression has been a dominant management practice in Southern forests, resulting in the extensive loss of habitat. The ecosystem is home to approximately 27 federally listed endangered species and 100 species of concern, including the Red-cockaded Woodpecker. With the ecosystem reduced to such a small and fragmented range, these species that are dependent on the ecosystem are at high risk to further population declines as longleaf pine forests continue to be threatened. Three major threats to the ecosystem are fire suppression as a management strategy, urban sprawl perpetuated by population growth in the Southeast, and climate change as it is likely to alter the fire regime in this important ecosystem.

Successful management of longleaf pine forests as a fire-depend ecosystem requires not only application of prescribed burns to mimic the natural fire regime and maintain longleaf pine tree dominance in the forest, but also incorporation of future societal changes, particularly the spread of development and urban sprawl, and projected climatic changes in future management strategies. Protection and recovery actions for the Red-cockaded Woodpecker as a federally endangered species have played an instrumental role in the management of large protected areas for longleaf pine success in North Carolina. While the single-species approach to management has proven highly successful for endangered species and any associated species with them, conservation of broad ecosystems like longleaf pine may require additional pieces to consider when prioritizing management actions. My goal for this project is to spatially assess current conditions and future projections for the three major threats to longleaf pine discussed here: fire management changes, climate change, and fragmentation and fire suppression resulting from urban sprawl.

I use red-cockaded woodpecker habitat requirements as a proxy to identify healthy longleaf pine patches in North Carolina that are unprotected and not managed with prescribed burning. I aim to identify longleaf pine patches that will likely be highly threatened and those likely to have the greatest survival and/or restoration potential given the current and future trends of these combined threats within the North Carolina historic range for the ecosystem. The hope is to identify longleaf habitat patches that may be prioritized for conservation and aid in successful restoration management of the ecosystem.

Background

Longleaf pine: a fire forest

Longleaf pine (*Pinus palustris*) forest is a fire-dependent ecosystem. The frequency and intensity of fires is critical, however, as infrequent fire allows hardwoods to take over and shade out herbaceous plant species that facilitate fire ignitions and spread (i.e., wiregrass). Hardwoods are susceptible to fire damage, particularly in early spring shortly after leaves start to bud. Thus, frequent understory fires keep hardwood growth low and longleaf pines are able to dominate (Van Lear 2005). More than 90% of plants in longleaf pine systems are perennials, many of which have extensive tap roots and underground stems so that they can survive when fire consumes the above-ground portion of the plants. Wiregrass responds to fire with abundant flowering following a burn. Longleaf pine trees also facilitate fire occurrence to perpetuate longleaf pine-wiregrass dominance: when the long needles from longleaf trees fall and rest loosely on top of the bunch grasses, circulating air keeps the fuel on the forest floor dry and creates optimal conditions for fire ignition and spread. The resins contained in longleaf pine needles also promote fire occurrence because they are highly combustible (Van Lear 2005).

A key species characteristic of longleaf pine is its thick bark that makes it resistant to fire and southern pine beetle outbreaks. The species' resilience to fire is also due to its adaptation strategies allowing it to regenerate in areas with frequent fire. First, longleaf pine germination requires bare soil, which small and frequent fires provide. Approximately a year after germination, the longleaf seedlings enter a 'grass' stage, during which the seedlings stop growing in height and allocate resources to growing more extensive root systems. The seedlings are vulnerable to fire for the first year, but once the seedlings reach the grass stage they are highly resilient to fire damage. Longleaf seedlings can persist in grass-like clumps resembling other bunch grasses for 3 to 25 years. Once seedlings have reached a diameter of approximately 1 inch, they then grow rapidly in height, as much as 4 to 6 feet annually. This growth strategy allows for the vulnerable growing bud to be exposed to high temperatures from fire for only a short period in its life cycle, giving the longleaf sapling a survival advantage from fires that kill or inhibit the growth of nearby hardwoods. In the adult stage, longleaf pine are highly resilient to fire, as the long flammable needles surrounding the bud direct fire away from it. The fire resilience of longleaf pine allows the species to dominate the forest as long as the fire regime that maintains it is allowed to continue (Van Lear 2005).

There is markedly high species diversity and endemism in the longleaf pine-wiregrass ecosystem. Species abundance tends to correlate with soil moisture because moist soils allow more rapid growth following a fire than drier soils. While species are fewer in drier longleaf zones, they are still relatively abundant compared to other ecosystems. . A fire return intervals of 1-3 years is necessary to maintain the openness of in the longleaf pine community. The decreased ground cover and pine needle litter in drier soil conditions creates less suitable conditions for fire, which can put these longleaf communities at risk because less frequent fire permits drought-tolerant hardwood species to become established in the mid-story (Van Lear *et al.* 2005). Wetlands embedded in longleaf pine ecosystems require periodic fire disturbance to maintain the open canopy in the wetlands as well as the ecotone between uplands and wetlands, which provide habitat for many rare plant species (Van Lear *et al.* 2005).

The Red-cockaded Woodpecker (*Picoides borealis*), a notable species dependent on the longleaf pine ecosystem, creates cavities in longleaf pine trees that are known to be used by at least 24 other vertebrates in the ecosystem. Another longleaf pine species, the pocket gopher (*Geomys pinetis*), creates complex burrow systems that host more than 80 species of arthropods, some of which are completely dependent on these burrows (Van Lear *et al.* 2005). Another example is the gopher tortoise (*Gopherus polyphemus*), which makes large burrows that have been documented to be used by over 300 invertebrates and 60 vertebrates in the ecosystem. A high number of longleaf pine animal species are considered of conservation concern: 18% of the amphibian species, 47% of the reptile species, 5% of the bird species, and 14% of the mammal species in states within the distribution of the longleaf pine ecosystem (Van Lear *et al.* 2005).

Fire in the Southeast

The South has the highest occurrence of wildland fires compared to other regions in the United States (Gaither *et al.* 2011). Biophysical features are critical factors in maintaining the high likelihood for wildland fires in the South: a longer growing season with frequent precipitation allows for abundant vegetation growth, a high frequency of lightning strikes, and the lack of a persistent snow layer. Drought is also a relatively common weather and climate extreme in the Southeast, and it is the foremost contributor to large wildfires occurring in this region (Liu *et al.* 2014). The interaction between weather, fuel, and topography in fire behavior (ignition, spread, and intensity of a fire) can be illustrated as a fire environment triangle (*Figure 1*). The role of each environment factor in fire behavior is described in Figure 2 (Liu *et al.* 2014).

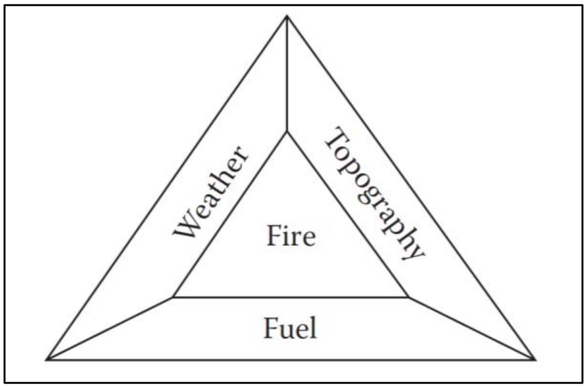
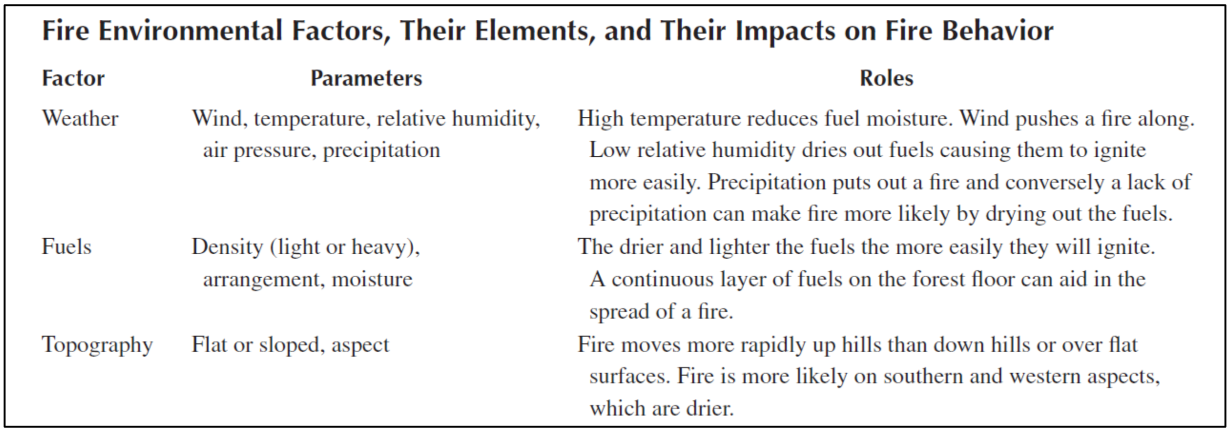


Figure 1: Fire environment triangle (Liu et al. 2014)



Fire Environmental Factors, Their Elements, and Their Impacts on Fire Behavior

Factor	Parameters	Roles
Weather	Wind, temperature, relative humidity, air pressure, precipitation	High temperature reduces fuel moisture. Wind pushes a fire along. Low relative humidity dries out fuels causing them to ignite more easily. Precipitation puts out a fire and conversely a lack of precipitation can make fire more likely by drying out the fuels.
Fuels	Density (light or heavy), arrangement, moisture	The drier and lighter the fuels the more easily they will ignite. A continuous layer of fuels on the forest floor can aid in the spread of a fire.
Topography	Flat or sloped, aspect	Fire moves more rapidly up hills than down hills or over flat surfaces. Fire is more likely on southern and western aspects, which are drier.

Figure 2: Fire environment factors and the role of each in fire behavior (Liu et al. 2014).

Wildfire has been shown to respond to weather variables, fuel conditions, and inputs from people. Human activities contributing to increased wildfire potential include fire prevention and suppression practices, and fuels management designed to reduce wildfire occurrence and spread (Liu *et al.* 2014). The widespread implementation of fire suppression programs within the last century was in response to the drastic loss of forest cover that came with the start of agricultural and industrial development during the nineteenth century (Gaither *et al.* 2013). Prior to industrialization in the South, Native Americans and early settlers set small frequent fires to reduce fuel loads. The longleaf pine fire regime before European settlement was characterized by frequent low severity understory fires with a return interval of 1 to 4 years (Liu *et al.* 2014). However, industrialization was followed by decades of fire suppression management, which has led to substantial fuel buildup in Southern forests. This buildup not only increases the risk of wildfire occurrence but also increases the intensity of fires when they occur and makes them harder to extinguish because they are burning in heavy fuels (Gaither *et al.* 2013, Liu *et al.* 2014).

Humans also increase fire occurrence by unintentionally starting fires and with land use changes affecting the fire frequency, location, and size of fires that occur (Liu *et al.* 2014). The South has a high population growth rate relative to other regions, including six of the fastest growing counties in the United States (Gaither *et al.* 2011). Population growth and increasing housing density contribute to an expanding wildland-urban interface (WUI), which in turn increases the likelihood of human-caused wildfire ignition due to the closer proximity to wildland areas (Gaither *et al.* 2011). Research has shown that wildfires tend to be clustered around human population, further supporting that wildfire ignitions by people increase with human populations (Liu *et al.* 2014). Urban sprawl also makes the implementation of prescribed burning for forest management more difficult, resulting in accumulating fuel loads and increased risk for high-intensity fires in the forests (Gaither *et al.* 2001).

Climate Change and Fire

Fire regimes are created by climate and fuel conditions, so changes in environmental conditions expected during this century are likely to alter fire regimes. The projected changes in climate, land use and development, social variables, and wildfire management practices in the coming decades make understanding the potential changes in fire regimes critical for assessing the possible impacts of future wildfire trends (Liu *et al.* 2014). The South is projected to experience warmer temperatures and, in many areas, drier conditions in the coming decades as a result of anthropogenic climate change (IPCC 2007). These changes in climate would contribute to prolonged fire seasons and increased fire frequency and intensity. This would likely result in larger total areas burned and more damaging burns, as well as changing fuel conditions with reduced fuel moisture from increased evaporation rates (Liu *et al.* 2014). The potential effects of climate change on fuel loads is more complex. Longer growing seasons may mean increased vegetation growth and thus increased fuel loading. However, a decrease in productivity and fuel loading could result from a reduction in water availability caused by higher evaporation and transpiration rates (Liu *et al.* 2014).

Projections for precipitation changes with climate change have a lot of uncertainty, but there is even greater uncertainty in how surface winds will change, which is a major factor influencing fire occurrence and spread. Surface winds are determined by topography such as surface roughness as well as spatial variation in thermal gradients from atmospheric heating, so prediction of changes in surface winds from climate change becomes even more difficult in areas with complex topography (Liu *et al.* 2014). The complexity of lightning occurrence makes it also a difficult process to predict future changes; lightning strikes could become more frequent due to increased temperatures and trends in atmospheric instability, but it is also difficult to project how significantly this could affect lightning-caused fire ignitions in the South (Liu *et al.* 2014).

The historical fire regime in longleaf pine forests where fires occur every 1 to 4 years illustrates the important role of forest management. To maintain such a regime, managers implement prescribed burns to reduce the frequency of large and devastating wildfire occurrence by reducing fuels accumulated in the forest understory. With the current fire potential at a moderate level and if prescribed burning is conducted every 4 years, the frequency of wildfire occurrence is approximately twice every 100 years. However, with projections of increasing fire potential from climate change, wildfire frequency could increase to three times every 100 years (Liu *et al.* 2014). To maintain wildfire frequency at twice every 100 years with the changes in climate conditions, the rate of prescribed burning would need to be raised to once every 2 years (Liu *et al.* 2014).

Recently developed models predict the overall impact of climate change on fire potential in the South is a gradual shift toward more severe fire conditions, due to the projections of lengthening spring and autumn fire seasons and increasing drought frequency and overall dryness during the summer across the South, particularly during the summer (Liu *et al.* 2014). Although models are in general agreement as to the impacts on wildfire potential trends resulting from climate change, many models are based on downscaled global climate models using regional climate models and so are typically not at a resolution capable of determining impacts on all important weather phenomena influencing fire potential and behavior (Liu *et al.* 2014).

Fire Management Tools

Fire disturbance is an important driver of landscape vegetation patterns in many ecological systems across the United States. Therefore, both understanding the underlying controls of fire dynamics and integrating that knowledge into geospatial representation of patterns across the landscape can play an important role in adaptive land management that will conserve both human and ecological communities

(Flatley *et al.* 2011). Flatley and his coauthors use GIS analyses to assess the influences of climate and topography as drivers of forest fire disturbance patterns. The authors note that understanding climatic and topographic drivers of fire pattern are complicated because fire response to these variables is not always spatially and temporally consistent, and these controlling variables can interact with each other. Previous studies have shown that climate influences fire regimes through its impacts on vegetation productivity and accumulation as fuel and through local weather that controls moisture levels. Topography contributes to fire patterns through variation in slope, aspect, and elevation; these directly influence precipitation and runoff rates, temperature, solar radiation, and air movement (thus controlling fuel accumulation and local moisture levels (Flatley *et al.* 2011).

Wildland fire management has increased in scope and complexity in recent years due to three combining factors: current climate trends, the infiltration of human communities and structures into wildlands, and increasing buildup of hazardous fuels due to management practices such as fire suppression (Ryan and Opperman 2013). The use of geospatial analysis as a means of understanding wildland fires and natural fire regimes has gained momentum in the last ten years as a tool for developing management strategies in fire-prone landscapes and reducing the risk of mega-fires across the United States (Hollingsworth *et al.* 2012). Ryan and Opperman describe the emerging trend of more frequent “mega-fires,” which refer to fires of unprecedented severity and/or size that can be devastating for people and natural systems and associated ecosystem services (2013). The threat of these mega-fires led to development of LANDFIRE, which is a GIS database and planning tool that allows GIS users to download data layers related to fire and use them to predict surface fire behavior for a given area in the U.S. (Ryan and Opperman 2013). The GIS data layers in the database include remote sensing images, soil and vegetation layers, topography layers, and meteorological data. The Southern Wildfire Risk Assessment (SWRA) also developed surface fire behavior models and canopy cover data specific to the southeastern United States (Hollingsworth *et al.* 2012). Specifically, the Wildland Fire Susceptibility Index (WFSI) is one of several indices produced by the SWRA that measures the probability of fire occurrence, fire behavior, and fire suppression effectiveness (Gaither *et al.* 2011). Managers can use these models at differing temporal scales to predict future fire behavior at a landscape-level spatial scale. The models also allow for land managers to look at and compare scenarios of different fuel treatments or fuel load conditions and the impact such variables could have on fire magnitude and spread (Ryan and Opperman 2013).

Red-cockaded Woodpecker Habitat Requirements

The Red-cockaded Woodpecker (RCW) has been listed as a federally endangered species since 1970 (ECOS 2014). The species is restricted to southern pine forests but indicates a strong preference for longleaf pine systems, particularly areas of pine with an open, park-like savanna structure with little hardwood understory (NatureServe 2014). Fire is recognized as a key factor in sustaining this habitat, specifically a fire interval of 1 to 5 years is considered necessary to maintain these forest habitats (Southeast Gap Analysis Project 2011). Perhaps the most outstanding habitat feature required for the Red-cockaded Woodpecker to inhabit a forest is that of old-growth pine trees, which are used for cavity excavation. Cavity trees are generally at least 70 years old, and trees infected with red heart fungus are often preferred, likely motivated by easier excavation, but these infected trees are typically the oldest trees in the forest (Southeast Gap Analysis Project). Cavities take up to a year to excavate but persist for many years and are used again and again as nest and roost sites. Even if habitat conditions are suitable in every way except for the lack of cavity trees, research indicates the woodpecker will very likely not occupy it (NatureServe 2014).

Evidence suggests that landscape features are important in maintaining good habitat quality for the RCW, such as habitat patch size and shape, foraging habitat total area, foraging habitat fragmentation, percentage and pinewood cover, and contiguity of forest canopy. While specifics for these habitat features are not entirely known, the growing body of research focusing on this issue provides some direction for identifying forest areas likely to provide good habitat (NatureServe 2014). NatureServe cites the minimum amount of land needed for a single group of RCW as between 40 and 160 hectares. The Southeast Gap

Analysis Project uses this range to define the 40 hectare minimum contiguous patch size used in mapping RCW range and distribution in the southeast. The authors also cite an elevation range between 0 and 850 meters. Stand density index (SDI) data can also provide useful forest attribute data for RCW foraging habitat criteria. SDI represents the number of 10-inch diameter trees per acre and can be used as an index of relative canopy density (Shaw and Long 2007). Although the preferred diameter for cavity trees has been documented as 14 inches, a diameter of 10 inches has been referenced to be used as a minimum size for cavity trees (Southeast GAP Analysis Project 2011). Therefore, an SDI of 1 is used as the minimum size density for RCW habitat. An SDI of 400 has also been used to approximate maximum size density for longleaf pine stands, which characteristically have an open canopy structure (Shaw and Long 2007).

The RCW Recovery Plan states that management for red-cockaded woodpeckers supports longleaf pine ecosystem protection, particularly because prescribed burning is a necessity in maintaining the open-canopy structure and preserving mature pines in longleaf pine forests (USFWS 2003). In this way, the single-species management of red-cockaded woodpeckers intersects with ecosystem-based management. The Red-cockaded Woodpecker is a uniquely suited species to characterize the longleaf pine ecosystem because of three main reasons: the RCW is an indicator species, as its population changes can mark the health of the ecosystem; it is an umbrella species, as its protection also provides protection for many associated species in the ecosystem; and it is a keystone species, in which its presence impacts the presence and/or abundance of other species in the system (USFWS 2003).

Objective

The purpose of this project is to spatially assess current conditions and future projections for the three major threats to longleaf pine (LLP): fire management changes, habitat fragmentation and fire suppression resulting from urban sprawl, and climate change. The structure of this paper is as follows: I first use RCW habitat requirements as a proxy to identify healthy longleaf pine patches in North Carolina that are not within designated protected area boundaries; using these unprotected LLP patches, I then distinguish those not currently managed with prescribed burning and thus are inherently at risk of encroachment from hardwoods; third, I isolate the unprotected LLP patches that are likely be highly threatened by urban sprawl between 2010 and 2100; and finally, I classify LLP patches by their relative habitat suitability and resilience given current and projected climatic conditions. I combine the resulting "threat maps" to identify longleaf pine areas likely to be at risk from any or all of these factors in the coming decades. I argue that the many acres of unprotected LLP identified by this geospatial analysis to be at risk of degradation from encroachment and/or climate change may be critically important in prioritizing areas for conservation and may aid in successful restoration management of the ecosystem.

Study Area

The study area includes the current distribution and historic range (potential habitat) for longleaf pine in North Carolina. The area extends from the eastern edge of the Piedmont through the Southeastern Plains and into much of the Middle Atlantic Coastal Plain (*Figure 3*).

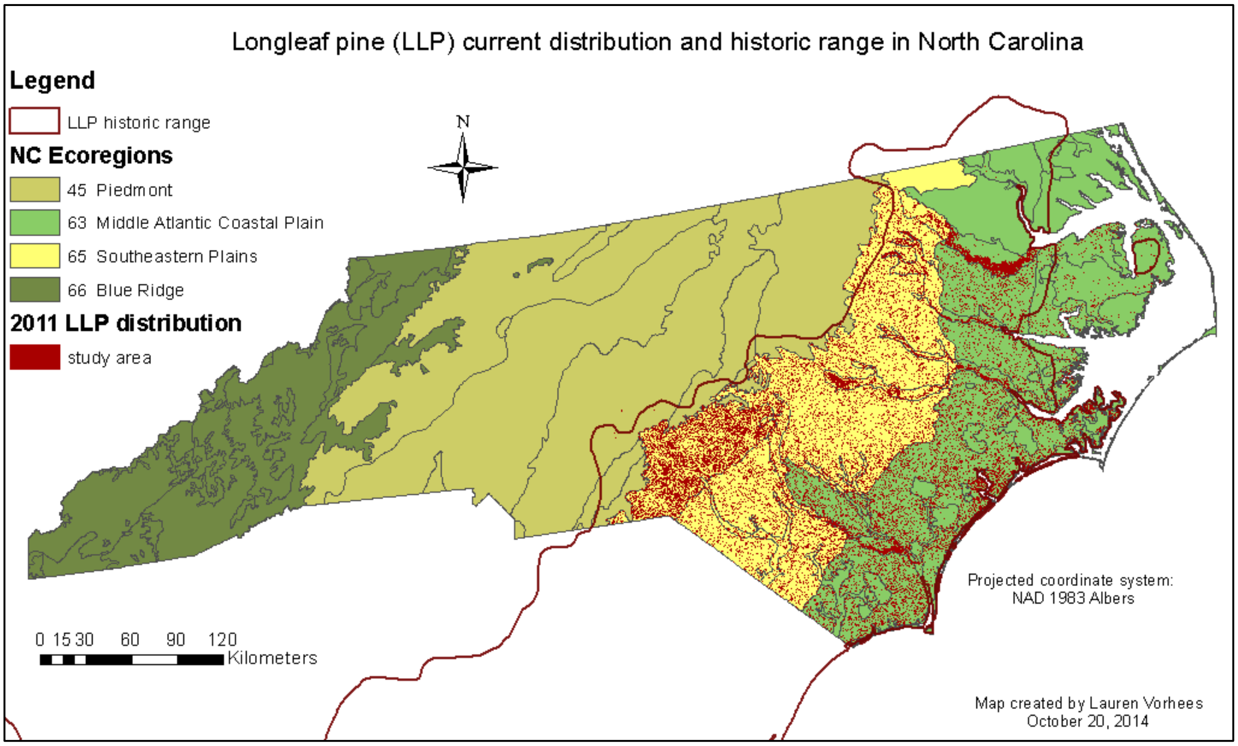


Figure 3. Longleaf pine study area in North Carolina, including the historic range and the current distribution based on USGS 2011 GAP Analysis Land Cover data.

Methods

For this analysis, I use geospatial analyses to examine major threats to the longleaf pine ecosystem in North Carolina. The first step in this analysis was to examine the existing range of longleaf pine within North Carolina compared to its historic range. To do this, I retrieved 2011 land cover data for North Carolina from the United States Geological Survey (USGS) National Gap Analysis Program (GAP) (*Figure A.1*). I utilized GAP land cover classes to extract the 7 Ecological Systems that contain longleaf pine in North Carolina (USGS 2011):

1. "Atlantic Coastal Plain Fall-line Sandhills Longleaf Pine Woodland - Open Understory"
2. "Atlantic Coastal Plain Fall-line Sandhills Longleaf Pine Woodland - Scrub/Shrub Understory"
3. "Atlantic Coastal Plain Upland Longleaf Pine Woodland"
4. "West Gulf Coastal Plain Upland Longleaf Pine Forest and Woodland"
5. "Atlantic Coastal Plain Fall-Line Sandhills Longleaf Pine Woodland - Loblolly Modifier"
6. "Southeastern Interior Longleaf Pine Woodland"
7. "Central Atlantic Coastal Plain Wet Longleaf Pine Savanna and Flatwoods"

Selection of these map units for Red-cockaded Woodpecker habitat is corroborated by the Southeast GAP Analysis Project (2011). These 7 land cover classes defined the current longleaf pine distribution for the study area for this analysis. All spatial analyses were performed in ArcGIS version 10.2 (ESRI 2014) using a 30 meter resolution. The geographic coordinate system used was NAD 1983 and Albers was used as the projection. All maps displaying intermediate data analysis results are included in the Appendix.

Longleaf Pine Habitat Analysis

Due to the strong link between recovery of the RCW population and restoration of the longleaf pine ecosystem, habitat requirements for the RCW may serve as a useful proxy to identify good quality longleaf pine habitat (Shaw and Long 2007). In order to identify longleaf pine patches that are suitable foraging habitat for the Red-cockaded Woodpecker (RCW), I referenced the habitat criteria listed in the RCW Recovery Plan (USFWS 2003). I first isolated the clusters of longleaf pine habitat cells and assigned each cluster a unique ID, yielding 667,483 patches (*Figure A.2*) with a combined total area of 2,687,066 acres or 1,087,420 hectares. The minimum contiguous patch size for RCW foraging habitat is cited as 40 hectares (Southeast GAP 2011).

With a 30 X 30 meter cell size, 40 hectares is equivalent to 445 cells, so I removed the longleaf pine patches that were smaller than 445 cells. This step yielded 3,030 individual patches (*Figure A.2*).

I downloaded elevation data from the USGS GAP database and forest attribute data provided by the USDA Forest Service (accessed through Data Basin). With the elevation dataset, I extracted the longleaf pine patches between 0 and 850 meters to meet the elevation criteria for suitable foraging habitat (Southeast GAP 2011). The forest attribute data included a Stand Density Index (SDI) layer, which indicates the total number of 10-inch diameter trees per acre (Krist *et al.* 2007). Red-cockaded woodpeckers require old growth pine trees for cavity excavation, so there must be longleaf pine trees present that are at least 60 years old in each patch. The SDI layer was also used to define a maximum longleaf pine size density because longleaf pine stands are characterized by an open canopy structure. To add these criteria to the habitat analysis, I extracted longleaf pine patches with SDI values between 1 and 400. Applying these habitat criteria yielded 2,798 patches (*Figure A.3*).

I retrieved GAP Protected Areas data (PAD-US) from the USGS Gap Analysis database and extracted protected areas for North Carolina (*Figure A.4*). PAD-US is an inventory of the terrestrial and marine protected areas in the United States, including all federal and most state conservation lands, as well as many regional and local protected areas (U.S. Geological Survey 2012). I made the assumption that habitat patches within protected areas will remain in protected areas, and therefore will not be threatened by encroaching urban sprawl. I used the protected areas in North Carolina to identify the longleaf pine habitat patches that are not within protected area boundaries, yielding 2,354 total unprotected LLP patches (*Figure A.4*).

Fire Management Analysis

To illustrate the spatial distribution of historical fire regimes within the study area, I downloaded LANDFIRE data of fire regime groups in the Southeast and clipped it to the North Carolina study area (*Figure A.5)*. LANDFIRE (Landscape Fire and Resource Management Planning Tools) is a cooperative project between the U.S. Forest Service, U.S. Department of the Interior, The Nature Conservancy, and other agencies. Its aim is to support strategic fire and resource management and planning across the United States (LANDFIRE 2014). The program produces large-scale geospatial data that describes vegetation, wildland fuels, and wildland fire regimes (South Atlantic LCC 2014). The Fire Regime Groups (FRG) is a data layer of fire frequency and severity classes based on interactions between vegetation dynamics, fire spread, and fire effects within a landscape (LANDFIRE 2014). To examine the Fire Regime Groups only within the unprotected LLP patches, I overlaid the FRG data with the 2,354 patch layer (*Figure A.5*).

With the historical fire regimes displayed for the longleaf pine patches, I then retrieved spatial data representing areas in the Southeast that are currently managed with prescribed fire (*Figure A.6*). The data layer used is one of the South Atlantic LCC indicators in the pine woodland, savanna, and prairies focal environment created using LANDFIRE data to quantify fire distribution in the southeastern U.S. (South Atlantic LCC 2014). I overlaid the longleaf pine land cover layer with the areas of habitat that are regularly burned and compared the resulting patches to the designated protected land layer for North Carolina (*Figure A.7*). Many of the longleaf pine areas that are regularly burned appear spatially to be clustered within protected areas, so I removed those clusters by intersecting this layer with the 2,354 unprotected LLP patches (*Figure A.8*).

Urban sprawl threat analysis

I retrieved urban growth prediction data from the Southeast Regional Assessment Project (SERAP) database (2011). The SERAP derived urbanization projections for the Southeast using the SLEUTH model, which was named for the input datasets for the model (Slope, Land Use, Excluded, Urban, Transportation, and Hillshade) (SERAP 2011). The model outputs provide projections for each decade from 2010 to 2100, but I chose three example years (2010, 2060, and 2100) to use in identifying longleaf pine patches that are likely to be highly threatened and those likely to be least threatened in this century. After clipping the urbanization data to North Carolina, I created raster layers for SERAP 2010, 2060, and 2100 containing only pixels of urban areas (*Figure A.9*). I created a similar raster using the 2011 GAP land cover dataset to compare to the SERAP 2010 layer to confirm similarity since the longleaf pine patches for Red-cockaded Woodpecker habitat were extracted from GAP land cover data.

I used the urban growth projections for these three SERAP study years to calculate distance from the urbanized areas followed by zonal statistics calculations to evaluate the minimum distances of each of the 2,354 unprotected LLP patches from urban sprawl. For each dataset year, I reclassified the minimum distance values into five distance classes using quintiles as the classification method. After confirming that the closest distance class for 2010, 2060, and 2100 contained only patches with a distance of 0 meters, I isolated the patches in this distance class for each study year in order to identify the longleaf pine patches whose boundaries are directly adjacent to urban development.

Climate change impact and resilience analysis

I retrieved Eastern United States Climate Tree Atlas data representing current and predicted suitable habitat for *Pinus palustris* (longleaf pine), created by the U.S Forest Service (Prasad *et al.* 2007). The data characterizes suitable habitat by importance values (IV), which were based on 38 environmental variables, including tree species data obtained from the Forest Inventory and Analysis (FIA), current climate conditions, and future climate projections for low and high emissions scenarios (Prasad *et al.* 2007). According to the Climate Change Tree Atlas, the predictions for *Pinus palustris* has high reliability (Prasad *et al.* 2007). However, this dataset has a 20 by 20 kilometer grid cell, so the data is highly generalized compared to the 30 by 30 meter grid cells in this analysis. Therefore, the dataset is used here as a general indication of the predicted spatial impact future climate conditions may have on longleaf pine forests. After clipping the data to the North Carolina study area (*Figure A.10*), I combined this layer with the 2,354 unprotected longleaf pine patches to examine their relative habitat suitability values in current and future climate conditions.

Longleaf pine has been described as a relatively resilient ecosystem to changing climatic conditions (Diop *et al.* 2009). I retrieved an ArcGIS data layer of from The Nature Conservancy's Southeast Resilience Project, which aims to identify important conservation areas based on land characteristics that increase diversity and resilience (TNC 2014). The final estimated resilience scores in the dataset were created by combining scores of landscape diversity and local connectedness, which were then prioritized based on the corresponding geophysical setting and ecoregion to the natural areas (TNC 2014). After clipping the data to the North Carolina study area (*Figure A.11*), I combined the layer with the 2,354 unprotected LLP patches (*Figure A.12*).

Results

Longleaf Pine Habitat Analysis

The longleaf pine habitat analysis aimed to identify longleaf pine patches that meet foraging habitat requirements for the Red-cockaded Woodpecker (RCW). The analysis started with 667,483 individual longleaf pine patches that were delineated from the 2011 GAP land cover data. After applying a minimum patch size of 40 hectares and forest attribute criteria listed for RCW foraging habitat, the longleaf pine patch count was reduced to only 2,798. Removing all patches within designated protected areas reduced the patch count moderately, resulting in a final 2,354 unprotected patches that meet RCW foraging habitat criteria (*Figure 4*). The combined total area of these patches is approximately 697,767 acres or 282,376 hectares.

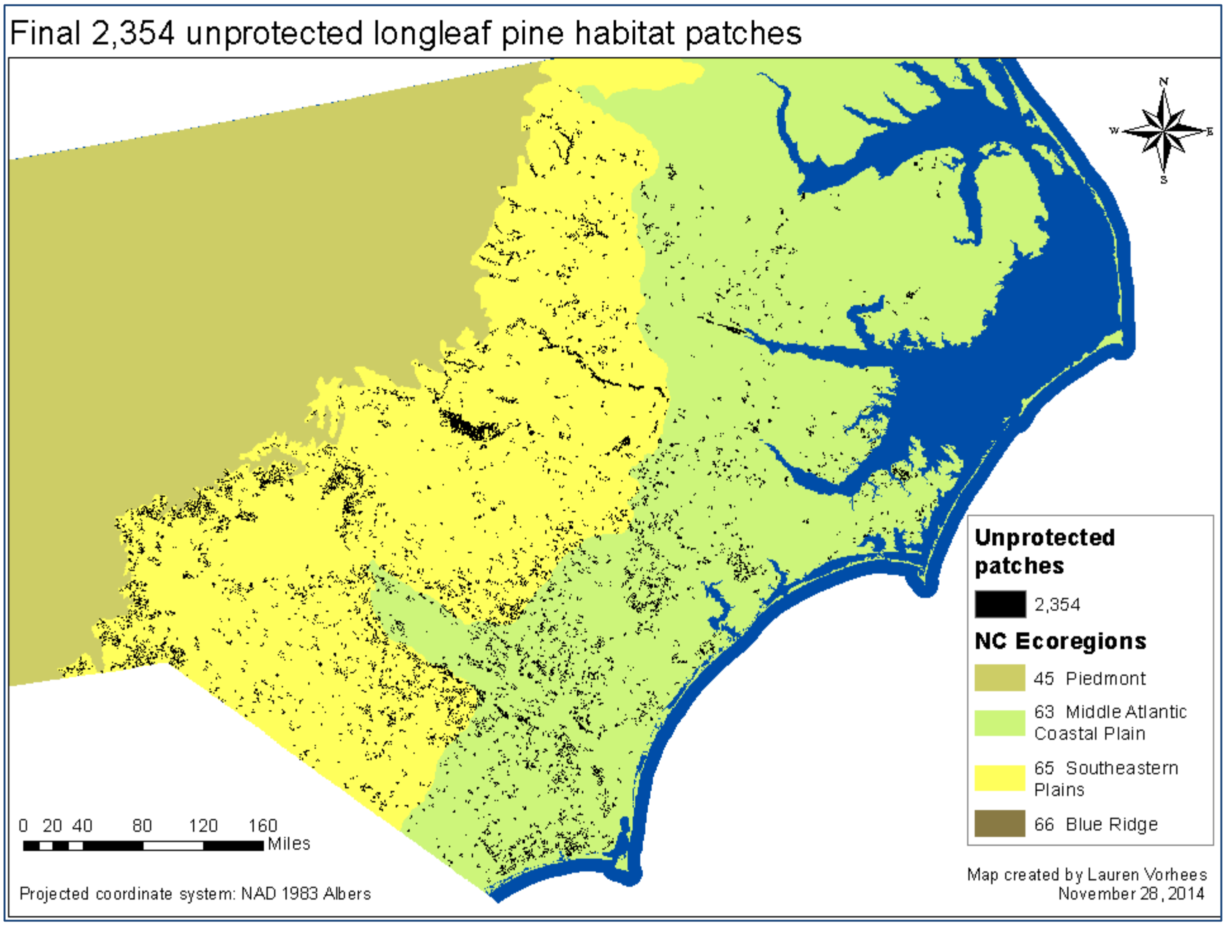


Figure 4. The final 2.354 LLP patches that meet criteria for RCW foraging habitat (USFWS 2003) but are outside protected area boundaries in North Carolina.

Fire Management Analysis

The 2,354 unprotected longleaf pine patches shown in figure 4 appear spatially to be categorized predominantly in Fire Regime Groups I and III (*Figure 5*). Both of these Fire Regime Groups are characterized by low and mixed fire severity, while FRG I has a fire return interval of less than or equal to 35 years and FRG III has a fire return interval between 35 and 200 years (*Table 1*).

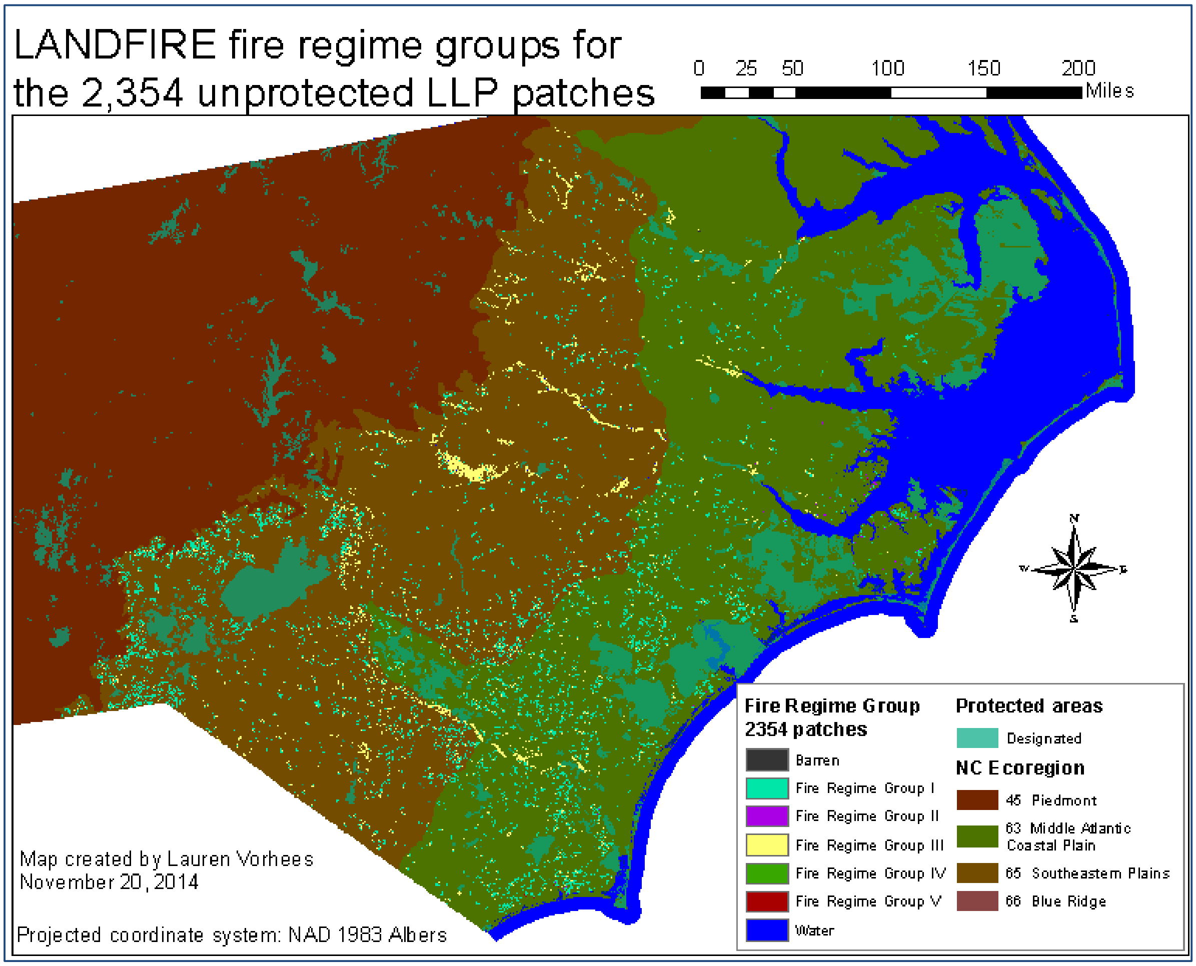


Figure 5. Unprotected LLP patches displayed by the corresponding Fire Regime Group (LANDFIRE 2014).

Table 1. Fire Regime Group descriptions

LABEL	**DESCRIPTION**
Fire Regime Group I	<= 35 Year Fire Return Interval, Low and Mixed Severity
Fire Regime Group II	<= 35 Year Fire Return Interval, Replacement Severity
Fire Regime Group III	35 - 200 Year Fire Return Interval, Low and Mixed Severity
Fire Regime Group IV	35 - 200 Year Fire Return Interval, Replacement Severity
Fire Regime Group V	> 200 Year Fire Return Interval, Any Severity
Water	Water
Barren	Barren

The South Atlantic LCC draft indicator dataset displaying open habitat that is regularly burned overlapped with 222,251 acres of longleaf pine forest in North Carolina (*Figure A.7*). However, many of these intersecting areas appear spatially to be clustered within the boundaries of designated protected land (*Figure A.7*). Removing those patches within protected areas yields a combined total area of 61,776 acres of regularly burned longleaf pine habitat (*Figure 6*). The collective area for the 2,354 unprotected LLP patches is 697,767 acres, which means only about 8.8% of those are being managed with regularly administered prescribed burns. With the remaining 635,991 acres of longleaf pine not managed with fire, I reapplied the 40 hectare minimum patch size, yielding 2,122 patches (*Figure 7*).

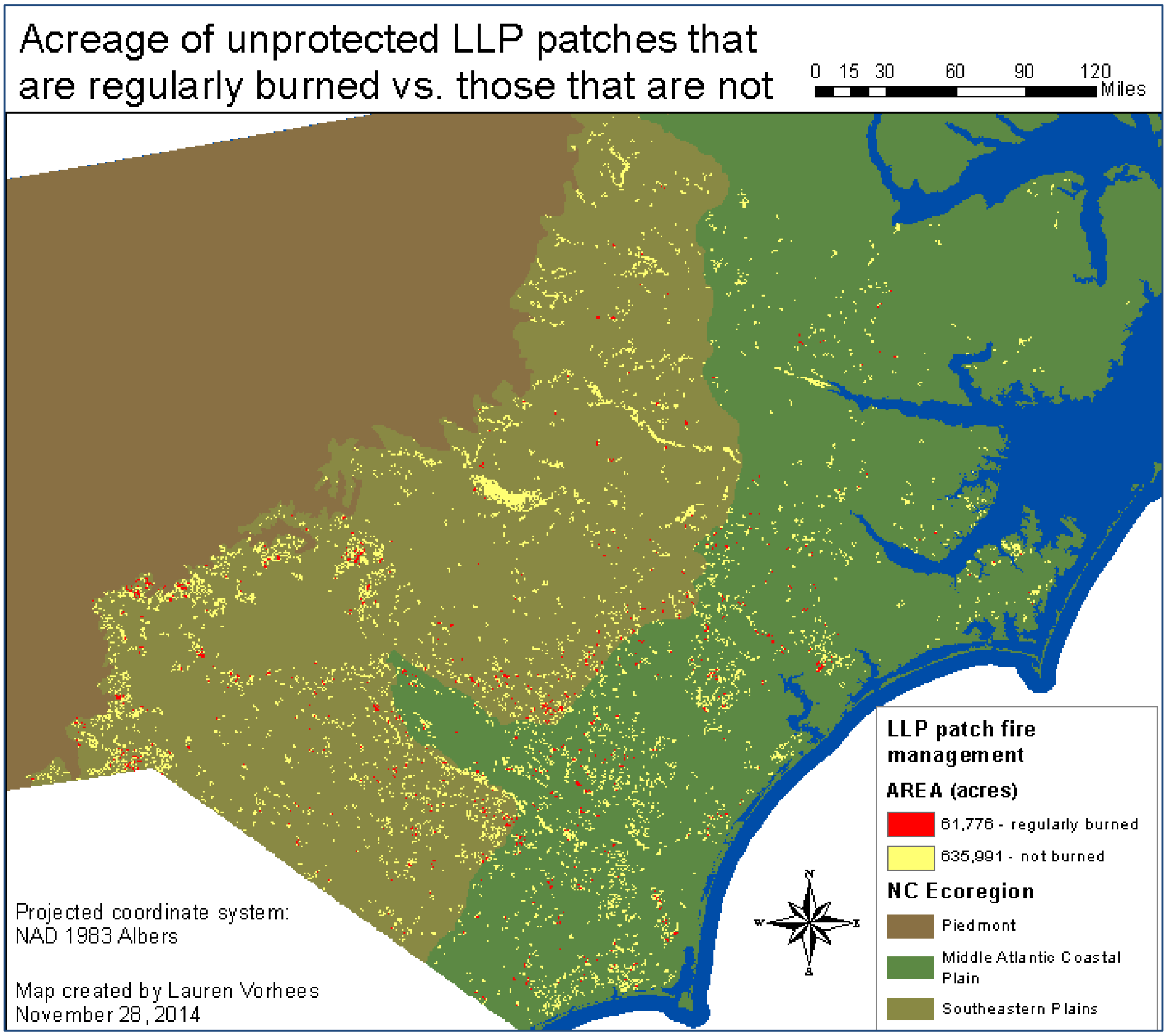


Figure 6. Unprotected LLP patches that are managed to be regularly burned (red) and all unprotected LLP patches (yellow).

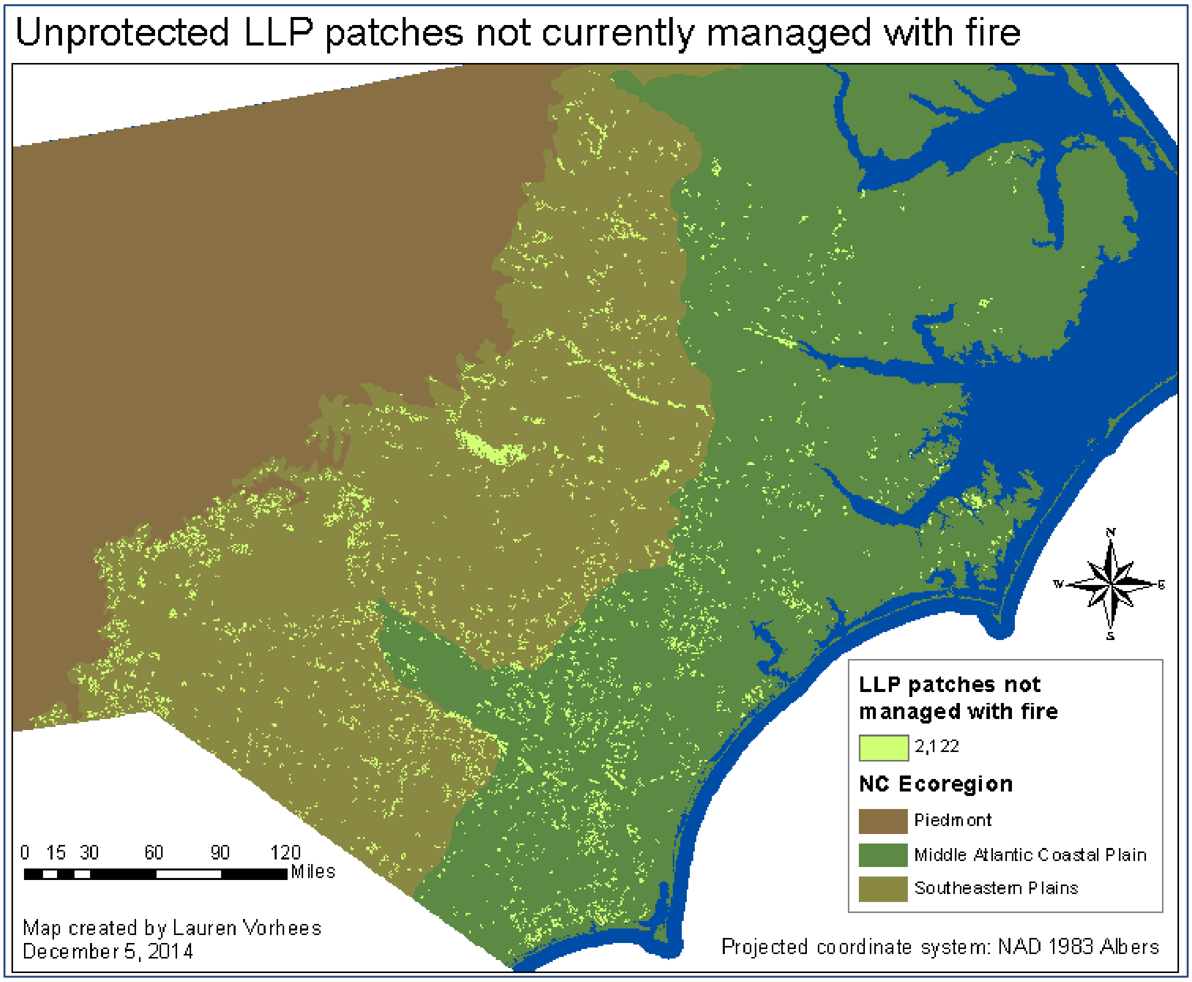


Figure 7. Unprotected LLP patches that are not currently managed with periodic fire.

Urban Sprawl Threat Analysis

The 2,354 unprotected LLP habitat patches shown in figure 4 are speckled across much of the Coastal Plains of North Carolina. One method of prioritizing these patches in terms of conservation efforts and resources is to evaluate the relative threat urbanization poses to each of these patches. Urban growth prediction data from the Southeast Regional Assessment Project (SERAP) served as the basis for classifying the patches into five distance categories for each of the three study years (*Figure 8*). The closest proximity class contains only patches with a minimum distance to urbanized areas of zero meters, which means that those patches are bordering urban development at some location along their respective boundaries. As such, I assumed that the longleaf pine patches in this category in 2010, 2060, and 2100 are highly likely to be threatened by urban growth. Comparison between study years of high urban threat patches indicates almost twice as many LLP patches are threatened by urban sprawl in 2100 than in 2010 (*Figure 9*).

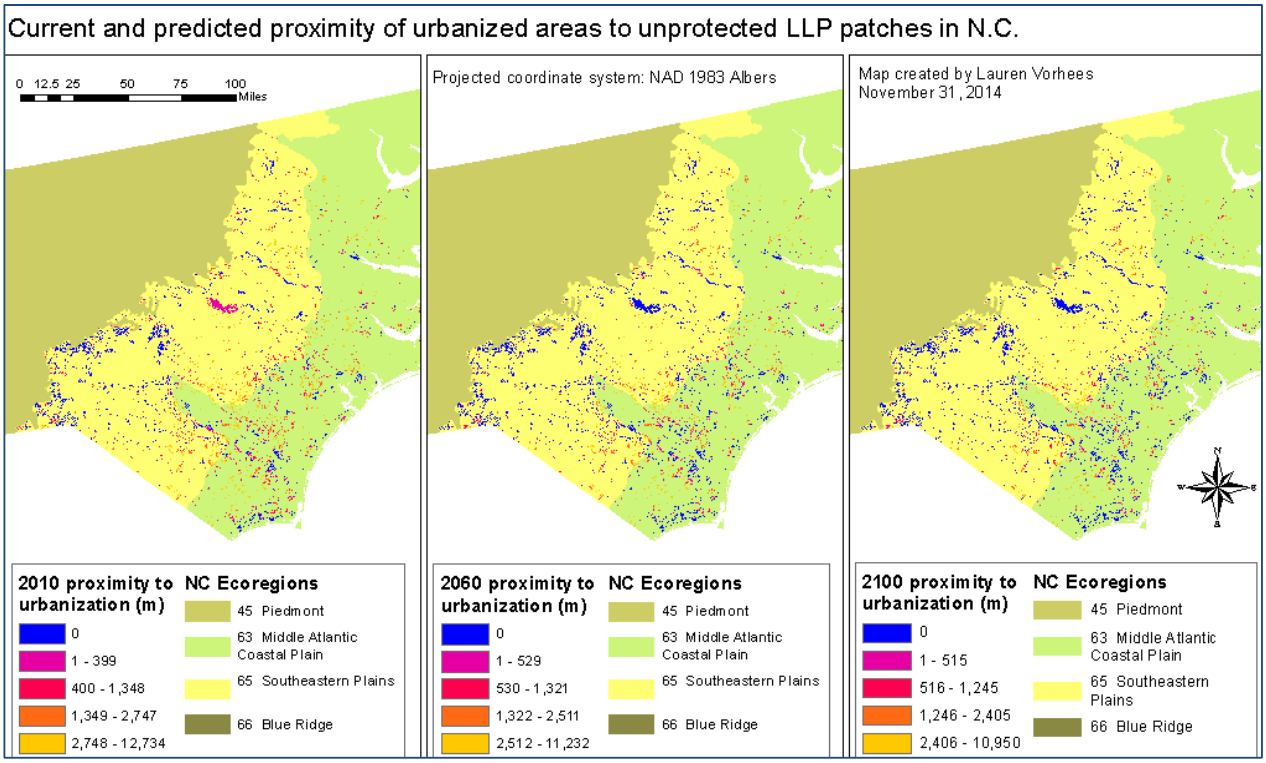


Figure 8. Unprotected LLP patches ranked by current (2010) and projected (2060 and 2100) proximities to urbanized areas.

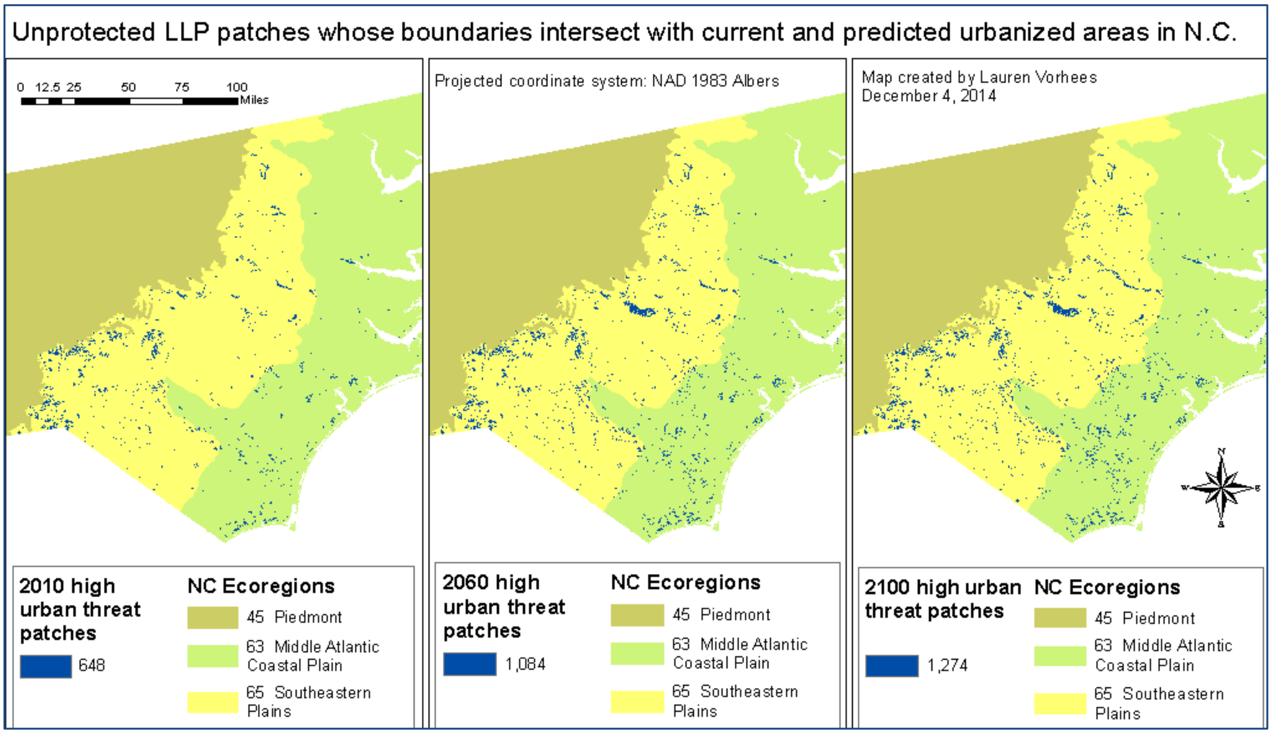


Figure 9. LLP habitat patches categorized in the closest proximity to urban areas for 2010, 2060, and 2100.

Climate change impact and resilience analysis

The Eastern United States Climate Tree Atlas data characterizes suitable habitat for longleaf pine by importance values (IV). These values were extracted for the 2,354 LLP patches for current climate conditions and future climate projections under low and high emissions scenarios (*Figure 10*). Many of the LLP patches with low importance values in current climate conditions appear to increase in habitat suitability in the future climate scenarios, while patches with high importance values in the current climate seem to decrease in habitat suitability (*Figure 10*). A clear trend is difficult to decipher based on these illustrated changes. However, as mentioned, the source dataset is used here as a general indication of the predicted spatial impact of climate change on longleaf pine forests. Based on these predicted importance values, it seems climate change is unlikely to have a substantial impact on North Carolina longleaf pine forests within the next few decades.

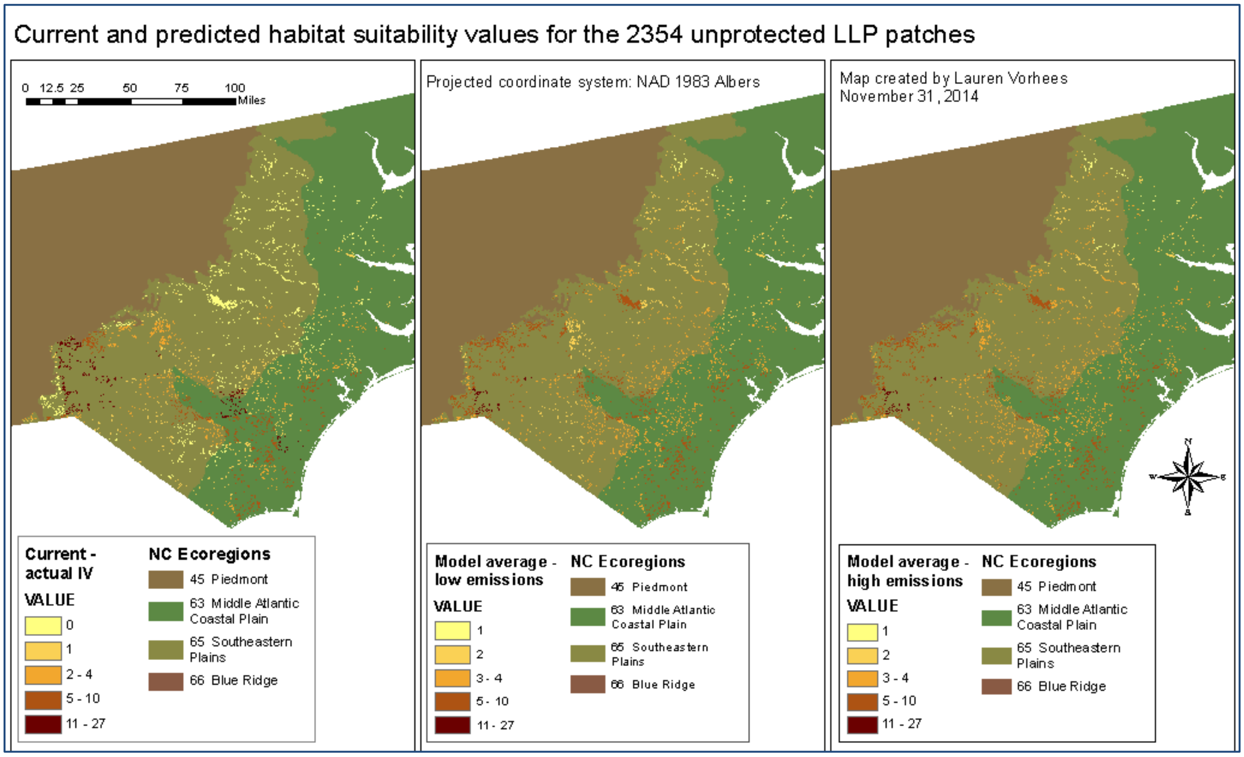


Figure 10. Habitat suitability for the LLP patches described by importance values (IV) in current climate conditions (left) and future climate projections under low (middle) and high (right) emissions scenarios.

Predictions of habitat suitability for longleaf pine indicate a possible increase in habitat suitability in some regions of the study area. To examine the climate resilience of these patches, I applied the climate resilience scores dataset from The Nature Conservancy's Southeast Resilience Project to the unprotected LLP patches (*Figure 11*). The resilience values were reclassified into 7 categories to match the original dataset from TNC, and then the patches were separated into 2 distinct classes for easy comparison: high resilience patches that include those in "above average" TNC resilience categories and low resilience patches that include those in "below average" TNC resilience categories (*Figure 12*). This step yielded 623 longleaf pine patches with high climate resilience and 409 patches with low climate resilience (*Figure 12*).

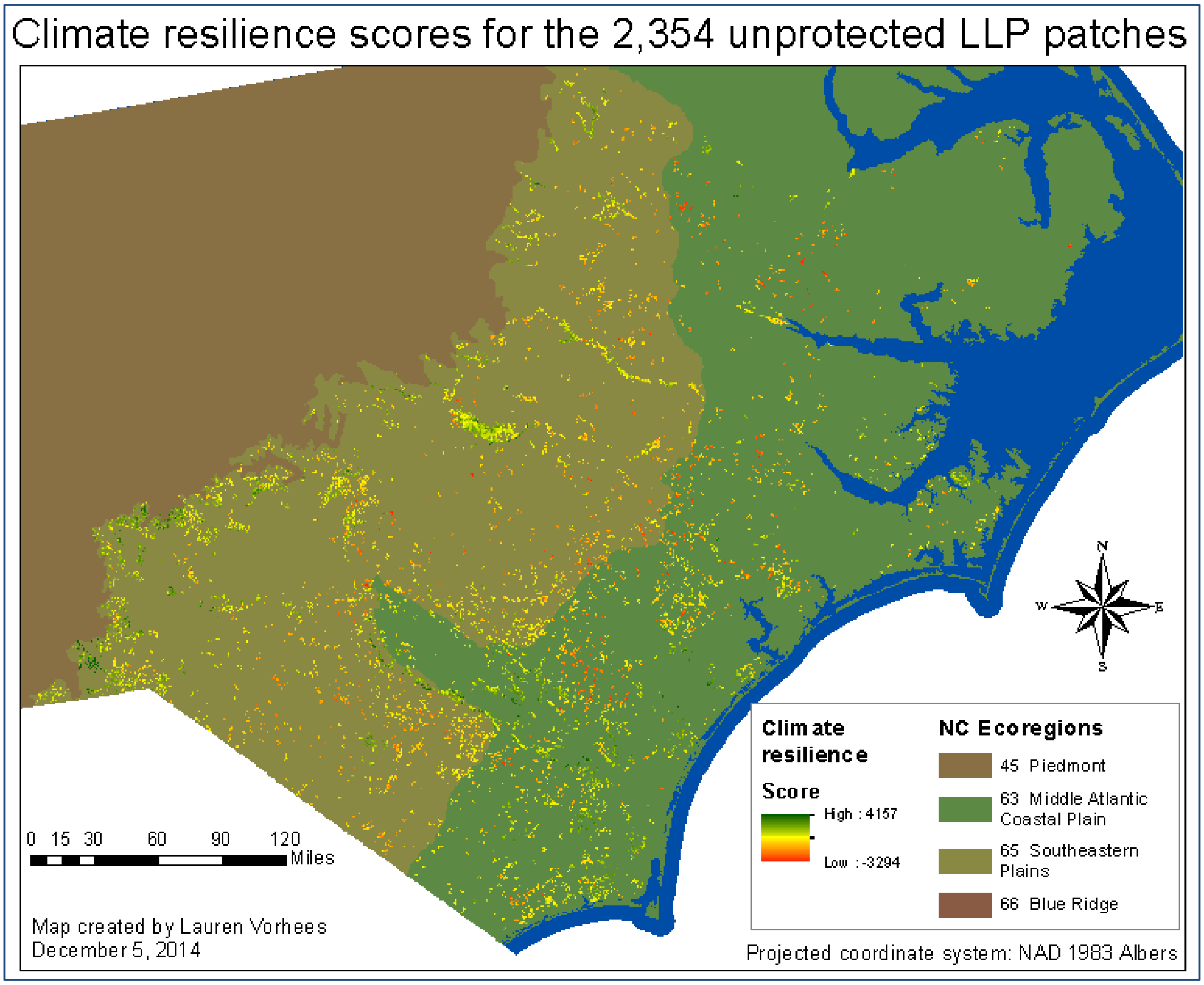


Figure 11. TNC climate resilience scores applied to the 2,354 unprotected LLP patches.

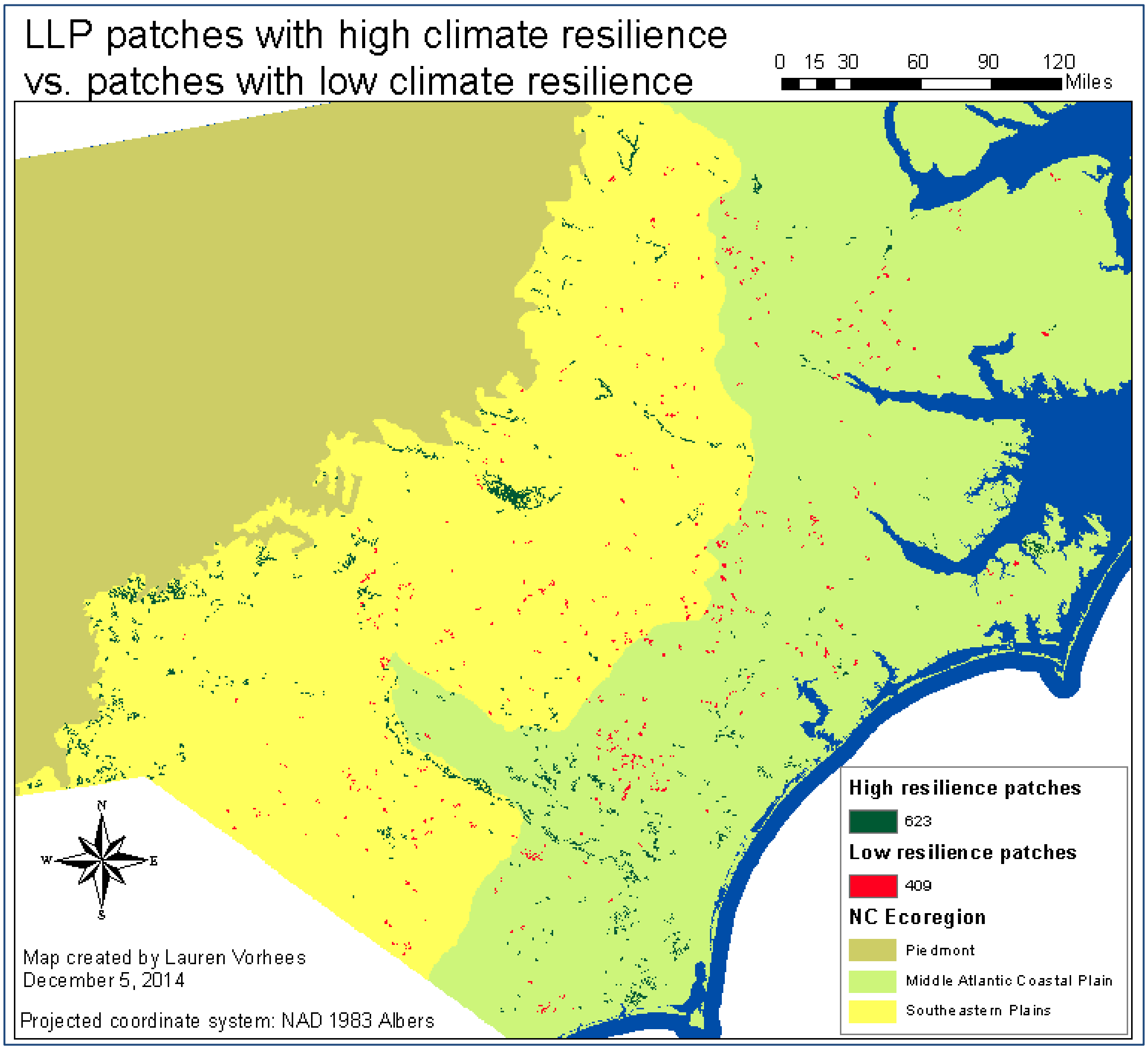


Figure 12. Unprotected LLP patches classified into high and low resilience categories based on climate resilience scores.

Synthesizing Results

The longleaf pine habitat analysis results were used to perform spatial analyses on three major threats to longleaf pine forests in North Carolina. I used the results from those analyses to produce three final threat maps: lack of prescribed fire, urban encroachment, and low climate resilience (*Figure 13*). Comparison of the threat maps side-by-side illustrates the relative patch counts, area, and spatial distribution of the three threats, with the greatest number of at-risk LLP patches resulting from lack of prescribed fire (*Figure 13*).

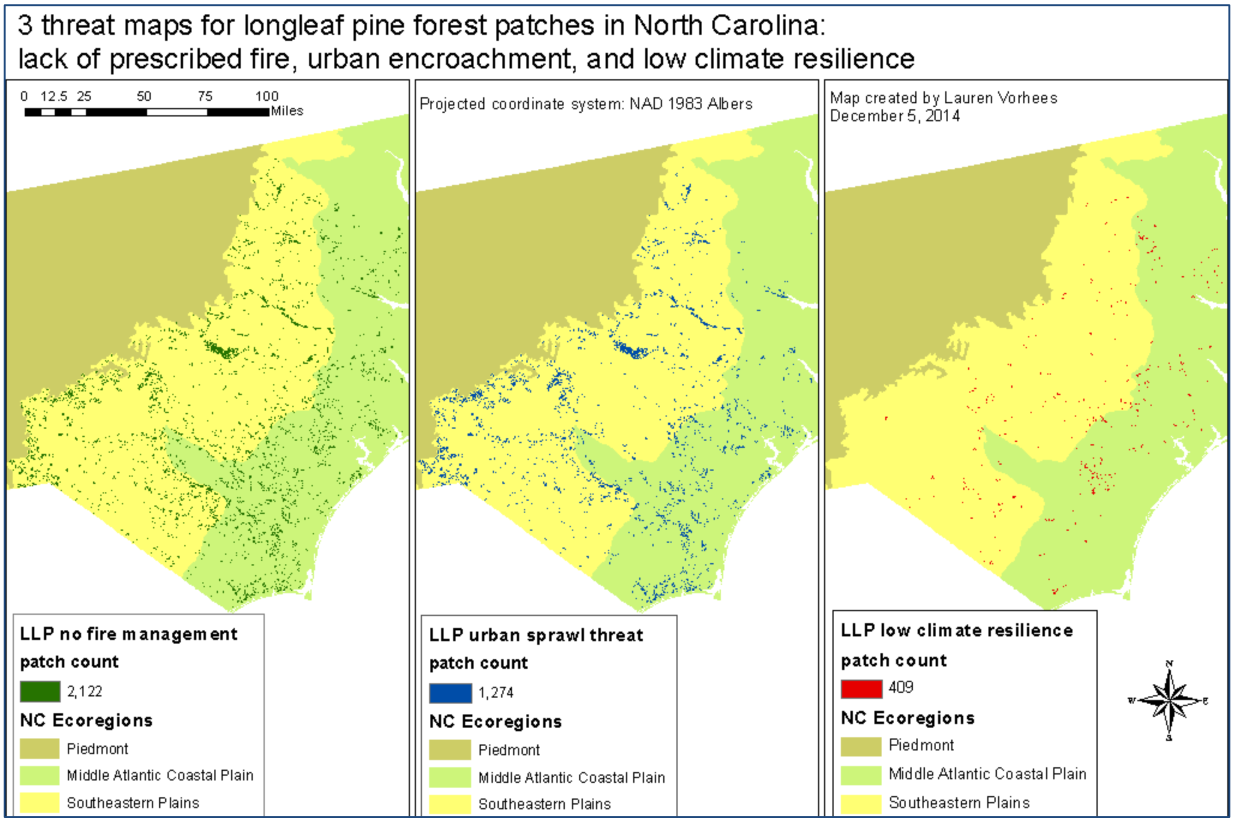


Figure 13. Comparison of the threat analysis result maps for the LLP patches.

Under the assumption that these threats have equal importance in longleaf pine persistence, I overlapped the three map layers to locate patches that are at risk from lack of fire, urban encroachment, and low climate resilience. This step identified 178 unprotected LLP patches that cover almost 30,000 acres and are highly dispersed across the study area (*Figure 14*). Alternatively, since climate change is not expected to considerably impact longleaf pine survival, a more accurate representation of at-risk longleaf pine may result if low climate resilience is considered to be of little importance for LLP persistence compared to fire management and urbanization. Under this assumption, I located the LLP areas that are not currently managed with fire and are likely to be threatened by urban encroachment, identifying a total of 1,168 patches covering 385,911 acres (*Figure 15*).

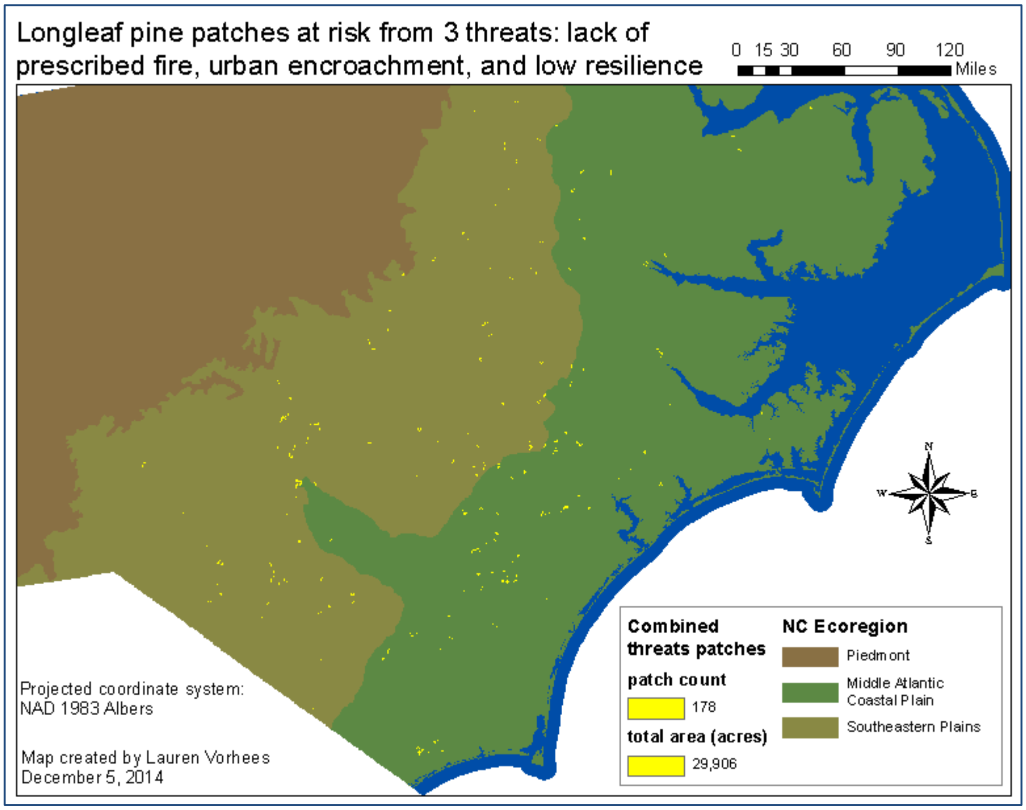


Figure 14. Unprotected LLP patch count and total area of patches identified in all three threat maps.

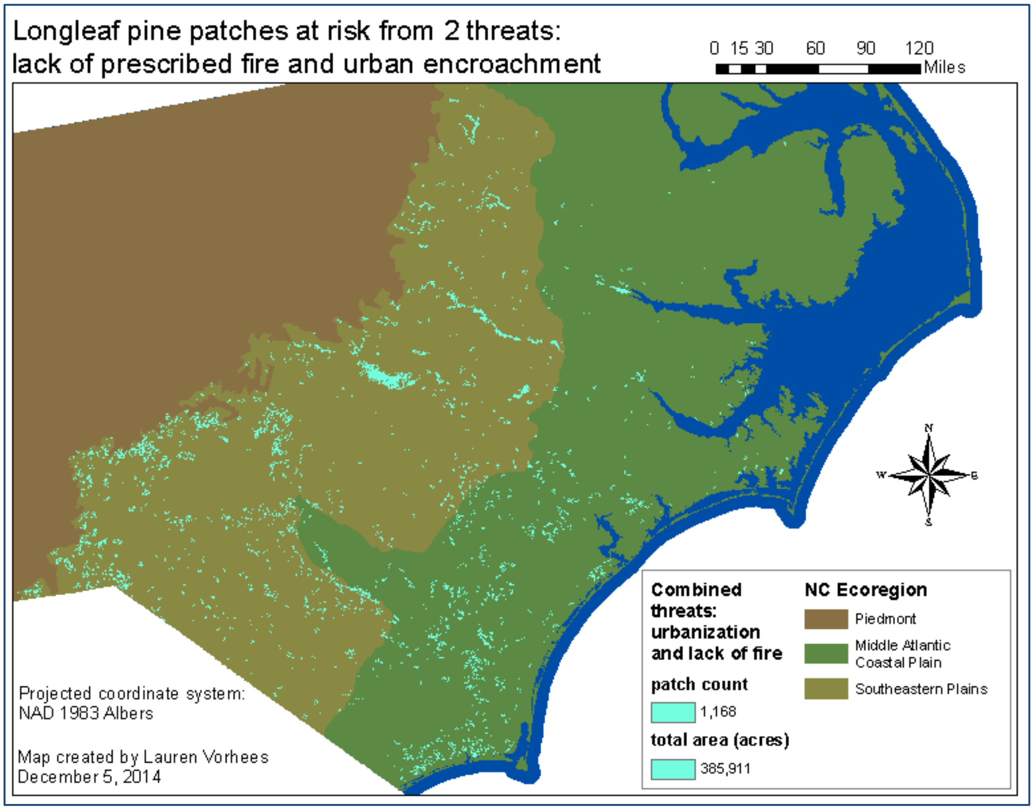


Figure 15. Unprotected LLP patch count and total area of the patches likely to be threatened by lack of fire management and urban encroachment.

Discussion

The longleaf pine habitat analysis identified 2,354 longleaf pine patches that meet the following criteria: have an area of at least 40 hectares, contain at least one old growth pine at least 10 inches in diameter (SDI $\geq$ 1), have an open canopy structure (SDI $\leq$ 400), and are located outside the boundaries of designated protected areas in North Carolina. The use of these criteria was based on measures used in previous studies of longleaf pine stands and Red-cockaded Woodpecker habitat requirements and availability of data. These criteria have been determined by other authors to be useful for maintaining consistency with the foraging habitat criteria listed in the RCW Recovery Plan (Southeast GAP Analysis Project 2011, USGS 2011, Shaw and Long 2007). While the criteria I used are consistent with those used in other studies, a major assumption in this analysis is that these criteria accurately identify viable longleaf pine patches to be used as inputs for the threat analyses. As such, incorporating additional habitat attributes that align with the RCW Recovery Plan Guidelines could improve the accuracy of the longleaf pine patch results.

Fire

A critical factor impacting conservation and restoration of longleaf pine is current fire management practices, as historical fire suppression in the southeastern U.S. has been a leading cause for the ecosystem's decline (Diop *et al.* 2009). Pressure from conservation organizations and the listing of federally endangered species that inhabit longleaf pine forests have contributed to significant changes in fire management within protected lands with the implementation of controlled burns (Diop *et al.* 2009). Prescribed burning of longleaf pine habitat is stated as a necessary management action for recovery of the Red-cockaded Woodpecker (USFWS 2003). Figures A.7 and A.8 in the Appendix illustrate the spatial distribution of regularly burned longleaf pine habitat in eastern North Carolina. The concentration of prescribed burning within designated protected areas is evidenced by the substantial decrease in total acres burned regularly after protected areas are removed from the map layer. The 61,776 acres of unprotected but regularly burned longleaf pine forest identified in the fire management analysis is less than 9% of the total area of the 2,354 unprotected LLP patches. This distribution indicates that, while prescribed burns are being implemented in protected lands successfully, the vast majority of longleaf pine stands outside protected area boundaries are not regularly burned. The forested land not managed with regimented burning are assumed to be managed with fire suppression. This divergence from the natural fire regimes puts these LLP stands at inherent risk from hardwood encroachment and catastrophic crown fires due to substantial buildup of forest fuels (Brockway 2005).

Although fire is accepted as an essential management tool for longleaf pine conservation and restoration, implementing this tool is often a complex societal issue as air quality concerns and rapid human population growth define the context in the Southeast. Land use changes including forest fragmentation, parcelization, and urbanization result in the creation of smaller and less efficient management units, which makes the application of prescribed fire increasingly difficult and expensive. Parcelization not only results in smaller parcels of forested land but also increases the number of landowners and management objectives (Burke *et al.* 2012). The expanding wildland-urban interface (WUI) that accompanies urbanization means closer proximity of forested land to residential areas and other development such as schools, roads, hospitals, and other infrastructure. This raises concerns of health and safety from smoke and fire, as well as increased liability risk from escaped fires (Burke *et al.* 2012, Fowler 2003).

The Clean Air Act requires that each State prepares a State Implementation Plan (SIP) specifying regulatory actions to limit air emissions from a variety of sources in order to protect air quality within the State (ALRI 2009). The smoke emitted from wildland fires contains high amounts of particulate matter and can impact air quality, so the State may include limitations on fire management practices in its SIP (ALRI 2009). Smoke management is particularly important near the WUI for protecting public health and welfare. Some significant longleaf pine forests are located near developed areas currently identified as high priority areas for visibility protection or as non-attainment areas for at least one criteria pollutant under the Clean Air Act (ALRI 2009). The analyses described in this paper include the spatial distribution of longleaf pine currently managed with fire and the proximities between developed areas and longleaf pine stands. A more comprehensive understanding of regulatory limitations to implementing prescribed burning might include the spatial distribution of the aforementioned federally-classified high priority areas.

Executing regular burns is also expensive. Restoring fire to longleaf pine across its range is complicated by significant financial constraints. For private landowners, the cost of applying fire at the frequency necessary to maintain longleaf dominance is too high, and most federal and state programs have insufficient financial incentives to address the issue (ALRI 2009). The training and experience required to execute the controlled burns can also be difficult for landowners to obtain. As a result, federal and state agencies have the most capacity to conduct prescribed burning, although there is a shortage of prescribed burning practitioners and services in many southern states (ALRI 2009). The shortage is due to budget constraints within the agencies as well as the financial risk and liability for escaped fires and smoke. The high cost of liability insurance is also prohibitive for independent consultants and service providers to fill the service gap (ALRI 2009). It seems clear that additional funding to federal, state, and local agencies and more financial incentives for private landowners will be a necessary part of increasing the total acreage of longleaf pine forest managed with fire.

Strategic changes may also be necessary, specifically to address the planning gap that often exists between suppression of wildland fires and the application of prescribed fires. For example, fires occurring between December 1 and March 1 are not destructive to longleaf pine, so in striving for efficient resource use, a wildfire igniting in a longleaf pine stand during those months could be taken advantage of by controlling the fire and not extinguishing it (Rauscher and Johnsen, eds. 2004). The creation of more integrated planning to achieve both objectives wherever the opportunity exists could increase cost efficiency of management efforts (ALRI 2009).

Urban sprawl

The urbanization threat analysis yielded 424 longleaf pine patches that were ranked in the highest urbanization threat class for all three study years: 2010, 2060, and 2100. The combined area for these threatened patches is approximately 366.1 km^2 or 90,465.3 acres, which is 13% of the total 697,767 acres within the 2,354 habitat patches in North Carolina. However, the projected 1,274 patches projected to be at high risk from urban growth in 2100 have a total combined area of 420,933 acres, which encompasses 60.3% of the unprotected longleaf pine areas currently in North Carolina. With the longleaf pine system already reduced to such a small and fragmented range, the ecosystem and threatened species that are dependent on it are at high risk to further population declines with continued habitat loss.

The South has changed dramatically in the last 100 years, shifting from a rural and agricultural-based society to a predominantly urban one. It is now one of the fastest growing regions in the United States, with projections indicating it will continue on the same trend in the coming decades (Rauscher and Johnsen, eds. 2004). The pattern of urbanization in the Southeast is characterized by sprawl and fragmentation, particularly in rural counties, which have been experiencing significant leapfrog development in recent years (Kaza 2013). With the expansion of urban development in the Southeast comes the expansion of the wildland-urban interface (WUI) and further fragmentation of the longleaf pine ecosystem.

The rapidly expanding WUI that accompanies urban growth is illustrated for North Carolina by the future urban sprawl projections mapped by the Southeast Regional Assessment Project (Figure A.9). The urban sprawl analysis for unprotected longleaf pine patches demonstrates the significance of urbanization as a major contributing threat to longleaf conservation in North Carolina. The most obvious impact between the study years (2010, 2060, and 2100) is the increase in blue patches, which indicates a proximity of 0 meters between those patches and urban areas (Figure 8). The use of proximity of each patch to urban encroachment clearly shows at a broad scale that urban development as an already significant threat to longleaf pine and one that will continue to grow rapidly in the coming decades.

Further analysis at a finer scale of the urban encroachment to longleaf pine areas could be useful for better quantifying the threat of urbanization to each LLP patch. My analysis, for example, illustrates urban proximity to each longleaf pine patch and the expected change in those proximities over time; however, additional data would be needed to distinguish whether a distance of zero meters indicates that the outer edge of the patch meets the outer edge of the patch or if part or all of the LLP patch has been destroyed and replaced by development. Similarly, the types of development that are near the longleaf pine patches is important for quantifying the threat urbanization poses to the patches, particularly in regards to the subsequent impact of development type on the fire management strategies that can be implemented in nearby LLP areas. Schools and hospitals are prioritized for protecting from smoke impacts, as are highways and other roadways that service high volumes and high traffic speeds (Miller and Wade 2003). As a result, the ability of land managers to implement prescribed burns in forests near such smoke-sensitive areas is extremely limited and sometimes prohibited (Miller and Wade 2003). Subdivisions are typically constructed without consideration of the potential of wildland fires, with the houses densely packed to maximize efficiency (Miller and Wade 2003). Such challenges add to the complex societal concerns surrounding fire management and implementation of restorative burns within the wildland-urban interface.

Some of the largest urban expansions for the Southeast are predicted to occur in the Blue Ridge, Ridge and Valley, Southern Coastal Plain, and Piedmont ecoregions (Terando *et al.* 2014). Since the distribution of longleaf pine spans much of the Southern Coastal Plain, these projections emphasize the potential threat of urban sprawl to the longleaf pine ecosystem in the future. It seems abundantly clear that the pressing threat of urban growth needs to be a substantial component to creating management priorities for conservation of the ecosystem and its imperiled species.

Climate change

I used the habitat suitability spatial data from the Climate Tree Atlas to examine the response of the longleaf pine study patches within North Carolina. These maps indicate that, under low and high emission scenarios, there is a general trend towards increased habitat suitability among most of the patches except for a cluster of patches on the western edge of the Southern Plains and a few clusters in the southern portion of the Middle Atlantic Coastal Plain. However, the species models from the Climate Tree Atlas are intended to be used as guidelines for regional trends, so the comparison of habitat suitability within the study area is used as a general indication of the level of threat climate change may pose to longleaf pine in North Carolina (Iverson *et al.* 2011). Thus, it may be concluded that the effects of climate change on longleaf pine are not likely to be directly detrimental to the species within this century. It is also important to note that it remains unknown what effects future climate variations will have on hardwood encroachment and canopy closure conditions in longleaf pine forests (ALRI 2009).

Currently, there are relatively few studies available that have compared the predicted climate change responses of eastern U.S. tree species. Therefore, the Eastern United States Climate Tree Atlas developed by the USDA Forest Service is one of the key sources available for such data (2007). The study compares current distributions to predicted distributions using relative frequency, density, and dominance of eastern tree species under four climate change scenarios predicted through 2100 (ALRI 2009). Results from this study indicate that, across its range, longleaf pine is predicted to respond better to climate change than all other southern pines and most deciduous tree species except for several southern oaks (Prasad *et al.* 2007). In fact, climate models suggest longleaf pine dominance may increase across its current range and might even expand its range northward (Prasad *et al.* 2007). The superior resilience of longleaf pine in these future climate scenarios may be explained by the species' ability to withstand drought and high temperatures. There is also strong evidence that longleaf pine is more resilient than other southern pines to damage from hurricanes and perhaps to southern pine beetle outbreaks. As tropical storms and hurricanes are expected to increase in frequency and severity in the coming decades with rising ocean temperatures, the resiliency of longleaf pine provides additional value to the successful conservation and management of the ecosystem (Diop *et al.* 2009).

Threat synthesis

My results from these three threat analyses demonstrate that fire suppression and urbanization pose substantial risk to the unprotected longleaf pine areas in North Carolina, while climate change is likely to have little to no negative impacts on these patches. Standing alone, the divergence from the natural fire regime currently puts the approximately 635,991 acres or 91.1% of unprotected longleaf pine that are not managed with periodic fire at high risk from hardwood encroachment and devastating crown fires. Urbanization in the study region currently threatens 648 of the 2,354 patches of unprotected longleaf pine, but future development is projected to threaten 1,274 of those patches by 2100, covering an area of 420,933 acres or 60.3% of all the longleaf pine outside of designated protected areas. Longleaf pine areas indicated as having low resilience to climate change expected within this century cover less than 9% of unprotected longleaf pine patches.

With the generally high climate resilience scores and the neutral to positive impact projected for habitat suitability with future climate change, I conclude that climate change is not likely major threat to longleaf pine persistence and should be excluded from the combined threat analysis. Under the assumption that the divergence from the natural fire regime and urban encroachment pose equal threat to longleaf pine persistence in North Carolina, approximately 385,911 acres or 55.3% of the North Carolina longleaf pine ecosystem is at risk from both of these threats.

Conclusion

Understanding the complex dynamics in a fire-dependent system like longleaf pine is essential for creating effective management plans for these threatened forests. However, a deeper understanding of the complex social context and community perspectives surrounding prescribed burns is also necessary for ensuring the health, resilience, productivity and safety of the longleaf pine ecosystem and the adjacent human communities (Williams 2004). In this analysis, I used geospatial analysis to examine fire suppression, urbanization, and climate change as three major potential threats to the longleaf pine ecosystem in North

Carolina. By eliminating designated protected areas and applying habitat requirements outlined by the USFWS for the endangered Red-cockaded Woodpecker (RCW), I was able to focus the study on unprotected longleaf pine stands with the potential for RCW habitation. Although it is now widely accepted that prescribed burning is a necessary management action for successful conservation of the longleaf pine ecosystem, results from this analysis indicate that less than 9% of the 697,767 acres of unprotected longleaf pine patches are currently being managed with regularly administered prescribed burns. Under the assumption that the remaining stands are being managed by suppression, this means that more than 90% of unprotected longleaf pine in North Carolina are at inherent risk from hardwood encroachment and/or devastating crown fires.

The necessity for prescribed burning in longleaf pine conservation is widely accepted in natural resource management fields. However, by integrating urban growth and climate change spatial projections with current fire-suppressed longleaf pine areas, this analysis provides insight into how critically important it is for managers to consider urbanization as an additional crucial threat to the longleaf pine ecosystem. As a naturally climate-resilient ecosystem, longleaf pine has increasing importance in regional conservation. With thousands of acres of unprotected longleaf pine forest not currently managed with fire and at high risk from urban encroachment impacts, targeting these patches for conservation prioritization and future fire management could considerably expand the extent of successfully managed and protected longleaf pine forests in North Carolina.

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Appendix A. Intermediate map analysis products.

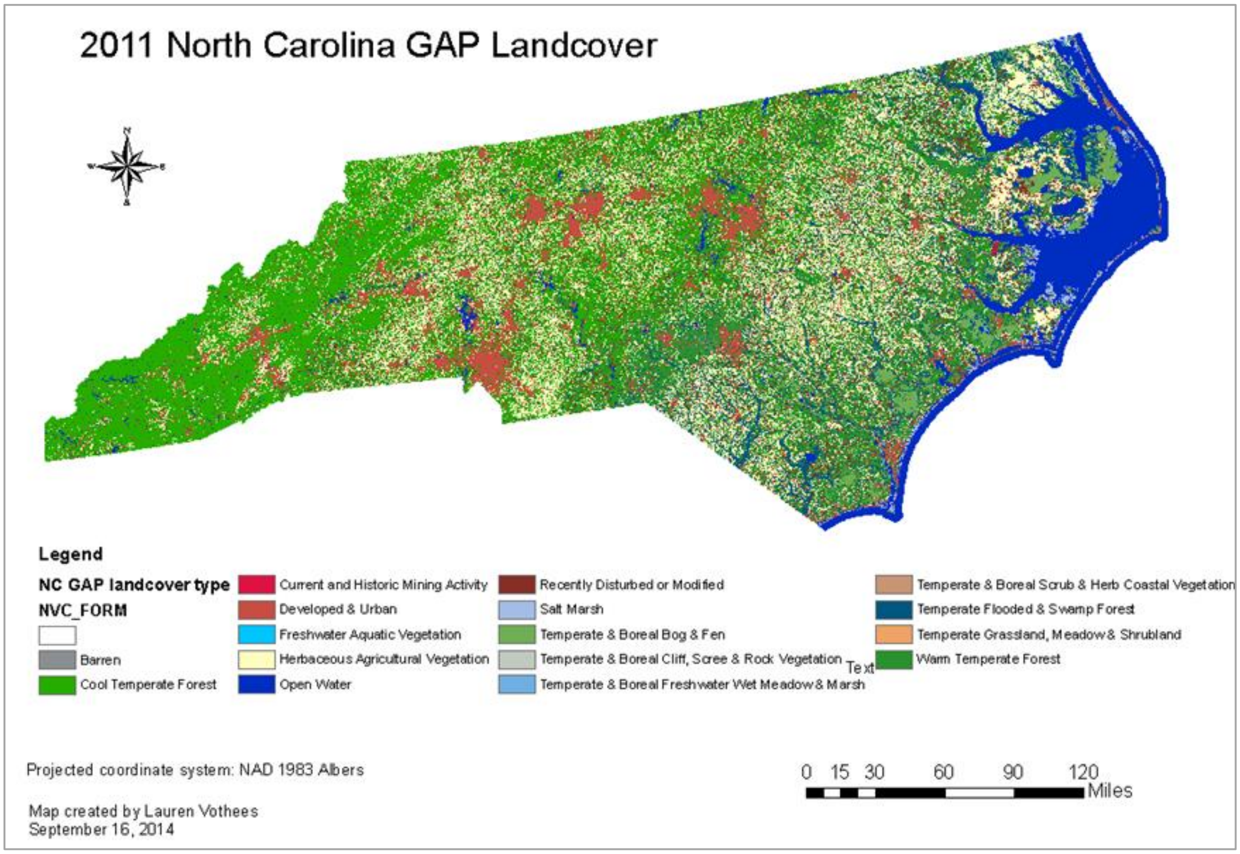

Figure A.1 - 2011 North Carolina GAP Land Cover data.

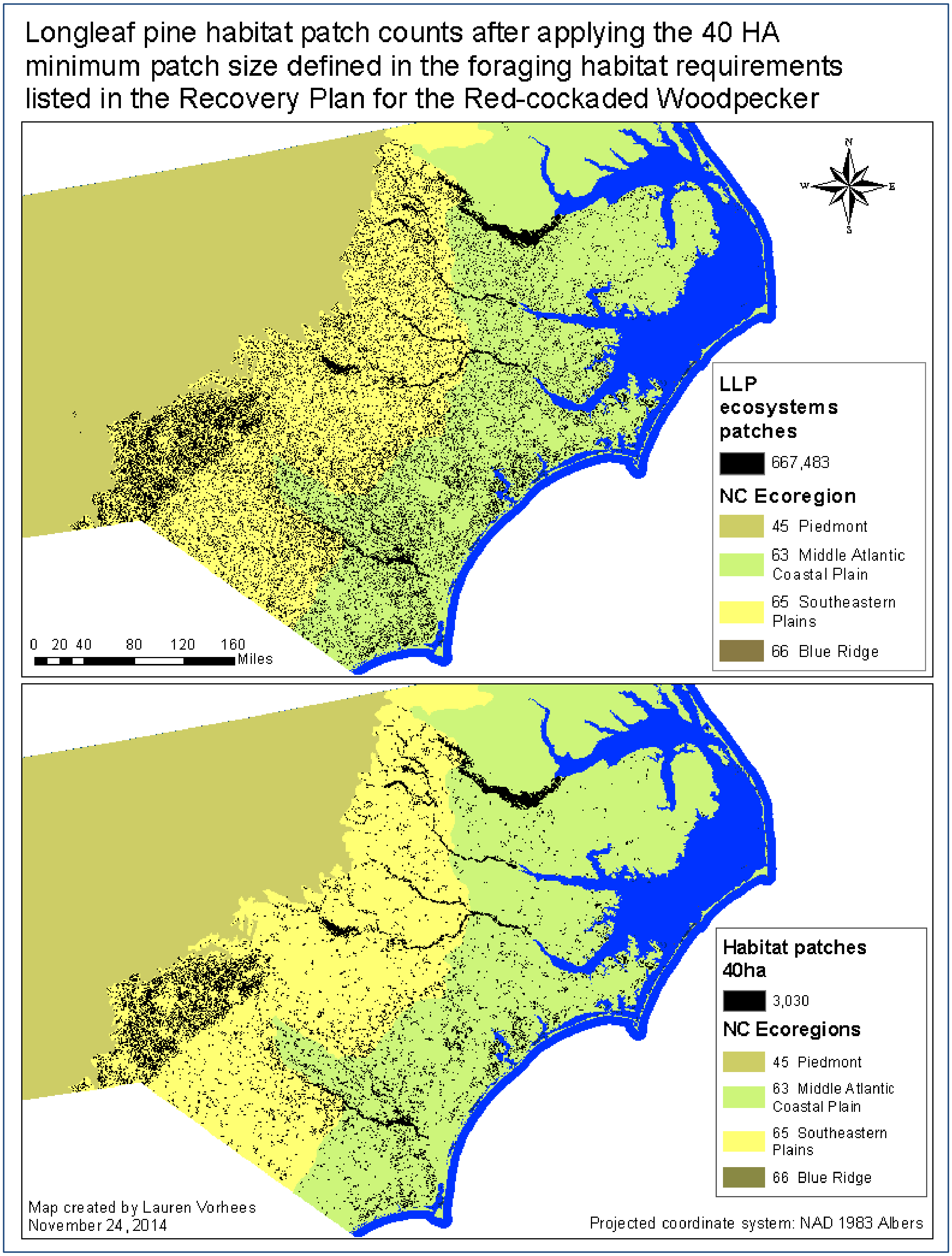

Figure A.2 - Longleaf pine habitat analysis intermediate results after applying foraging habitat criteria for the Red-cockaded Woodpecker (USFWS 2003).

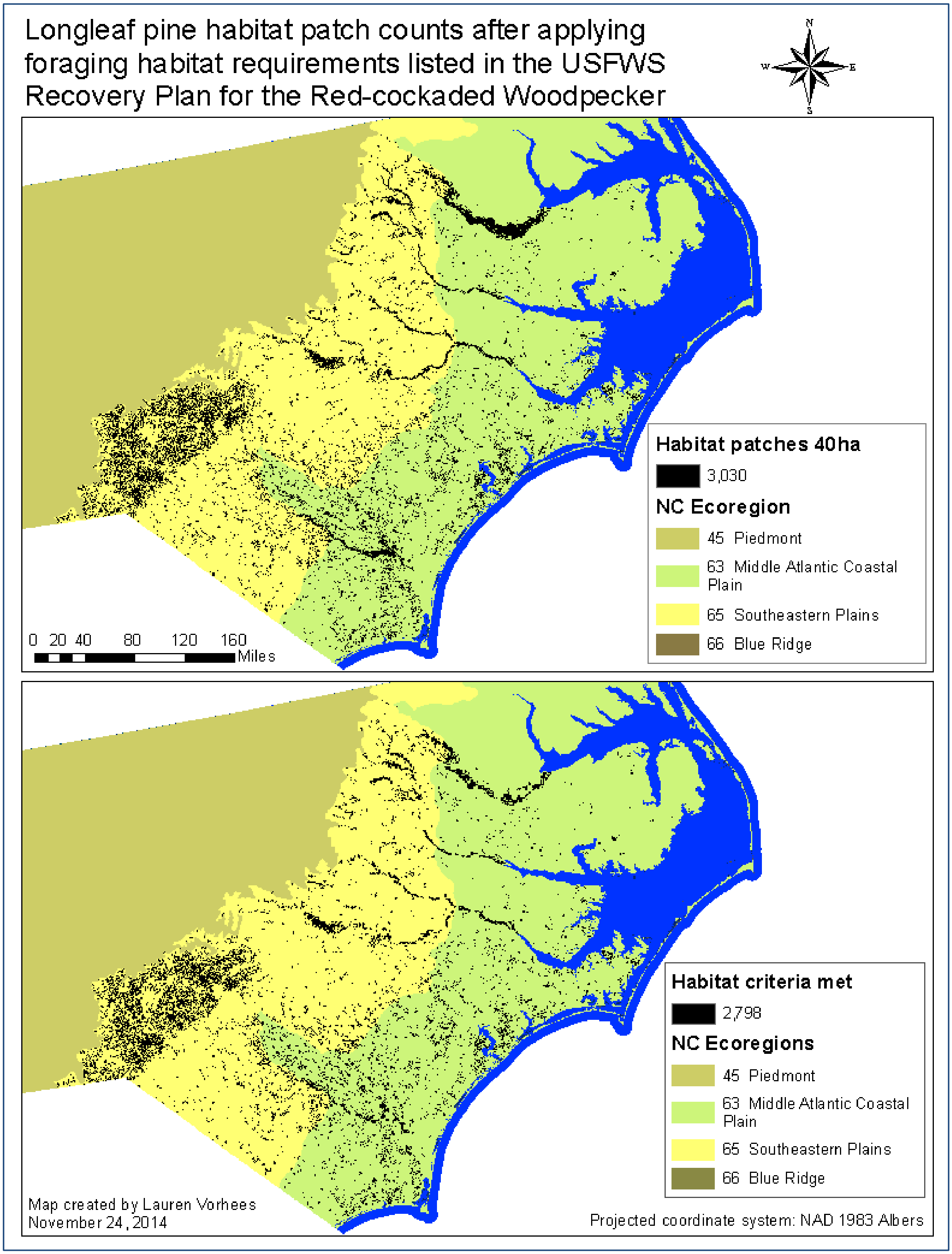

Figure A.3 - The 3,030 40-HA longleaf pine patches (top) vs. the 2,798 patches identified after applying foraging habitat criteria laid out in the Recovery Plan for the RCW (bottom) (USFWS 2003).

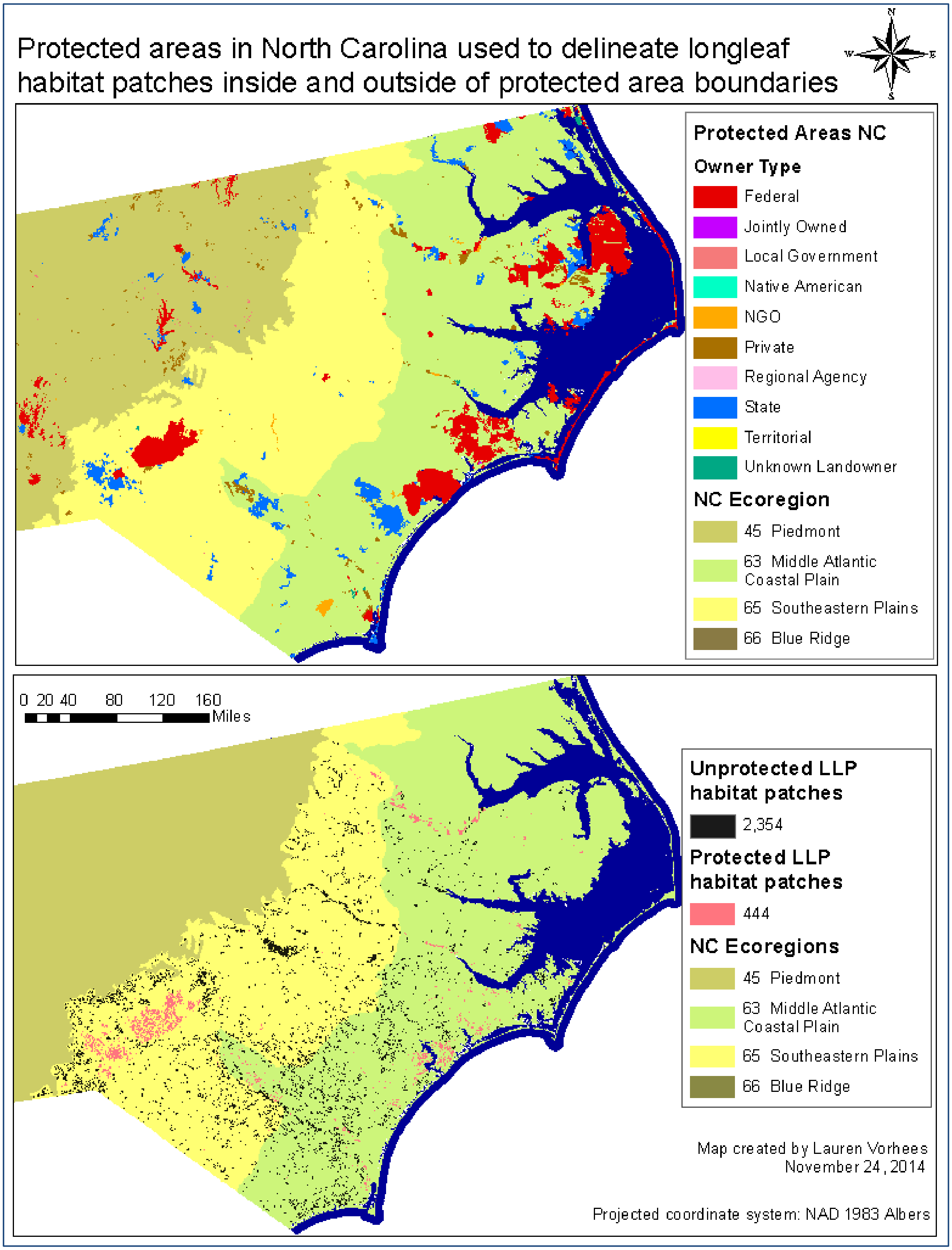

Figure A.4- Longleaf pine habitat patches that fall within the boundaries of designated protected areas that are removed from the next steps in the analysis.

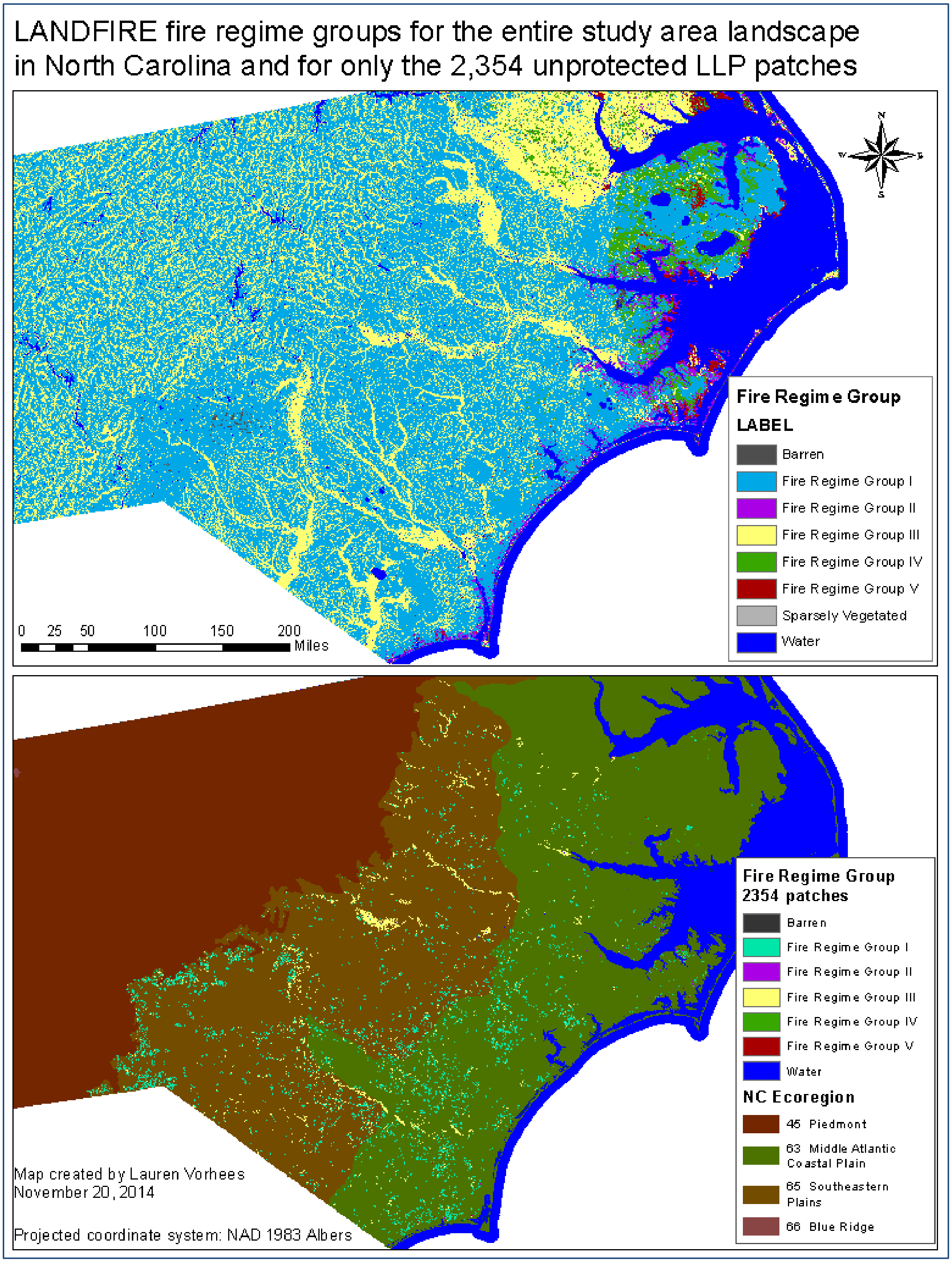

Figure A.5 - LANDFIRE fire regime groups for the entire study area landscape (top) vs. LANDFIRE fire regime groups for the 2,354 unprotected LLP patches (bottom).

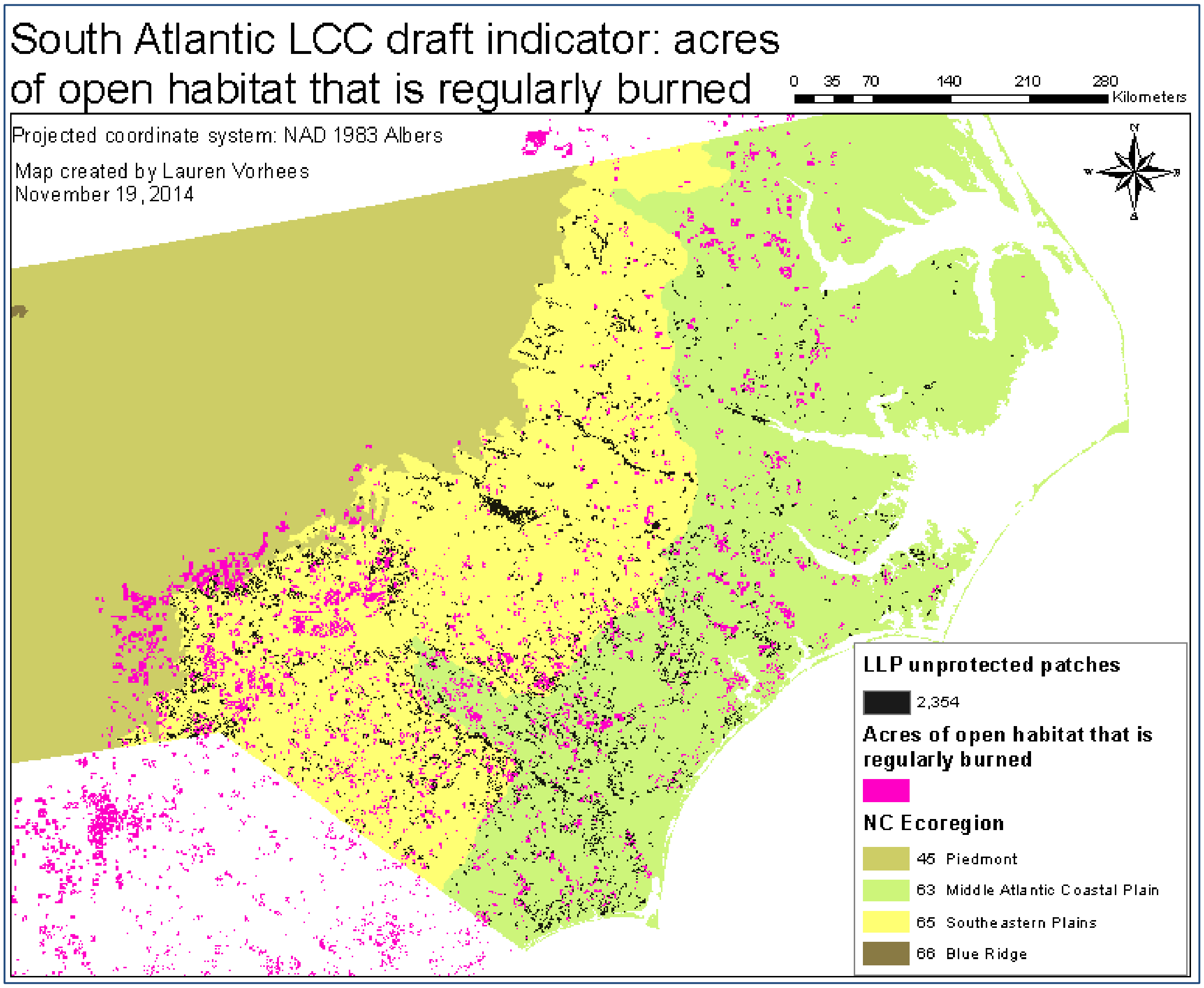

Figure A.6 - Acres of open habitat that is regularly burned overlaid on the unprotected longleaf pine patches layer.

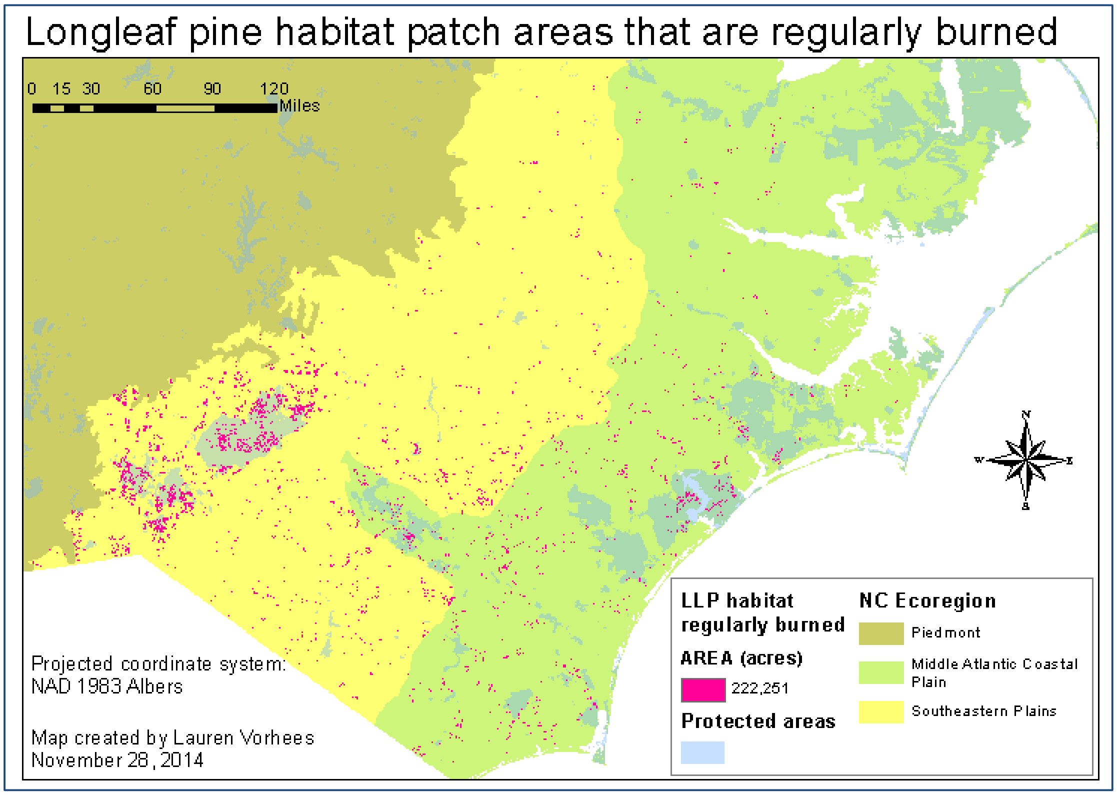

Figure A.7 - Acres of open habitat that is regularly burned that intersect with longleaf pine, overlaid on the designated protected land layer.

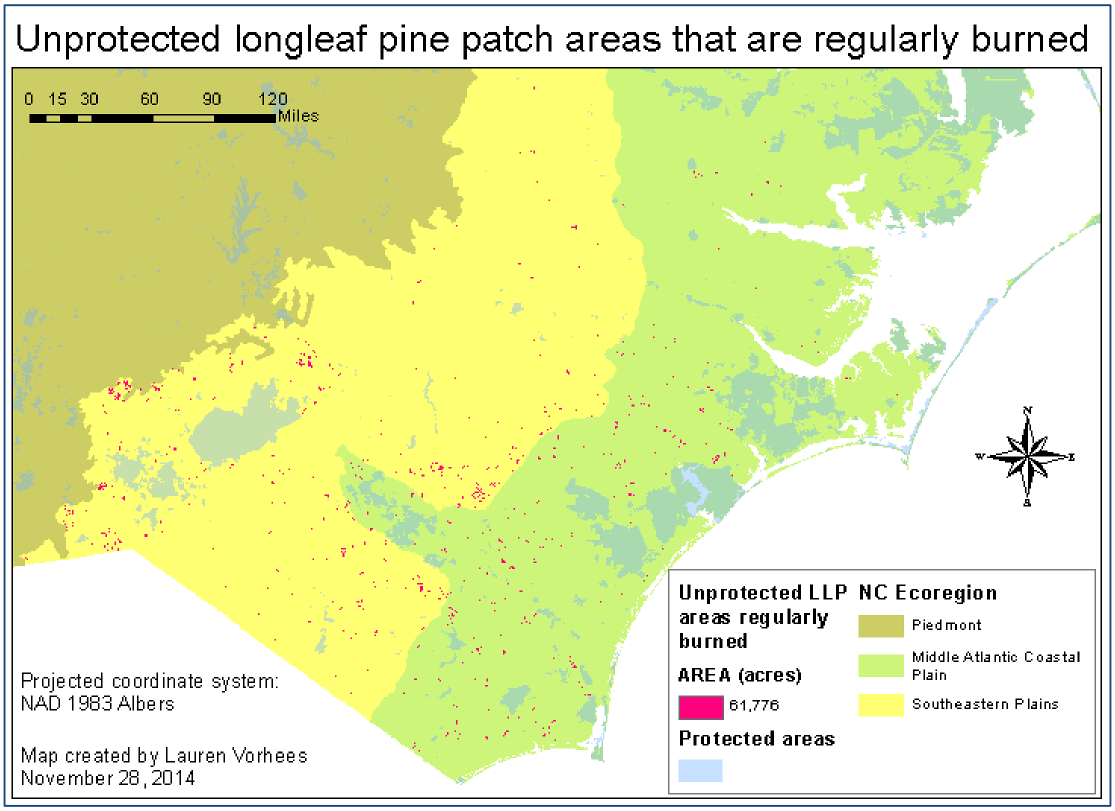

Figure A.8 - Unprotected LLP patches that are managed to be regularly burned.

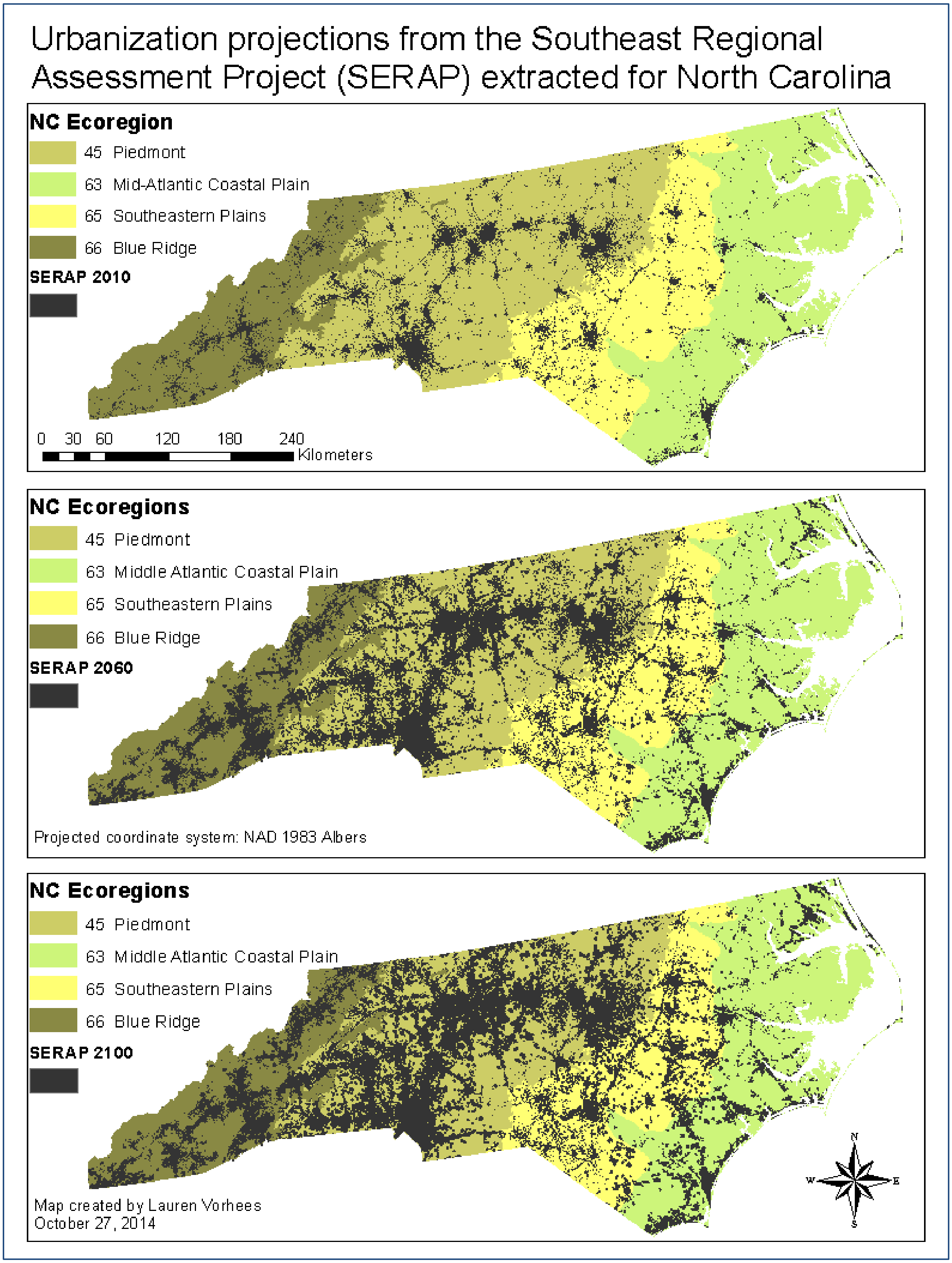

Figure A.9 - Future projections for urban sprawl in North Carolina, derived by the Southeast Regional Assessment Project using the SLEUTH model (SERAP 2011).

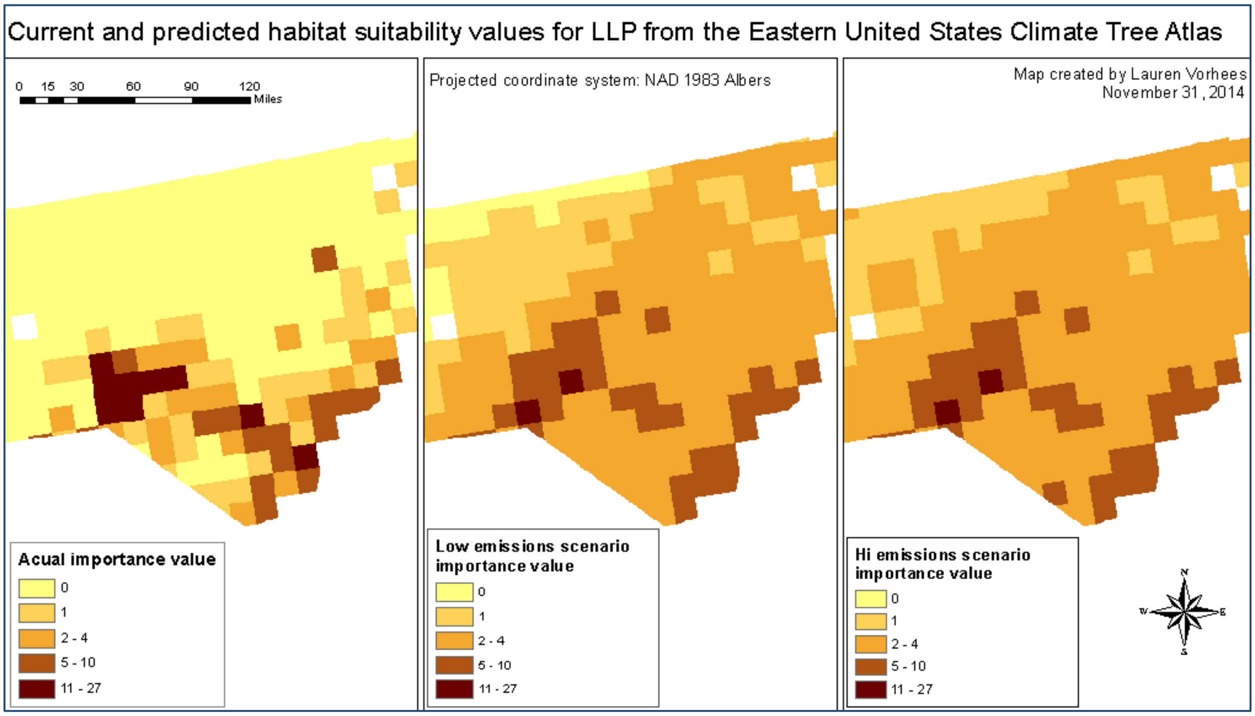

Figure A.10 – Current habitat suitability and predicted suitability under low and high emission scenarios for areas of longleaf pine in North Carolina, accessed from the Eastern United States Climate Tree Atlas by the US Forest Service.

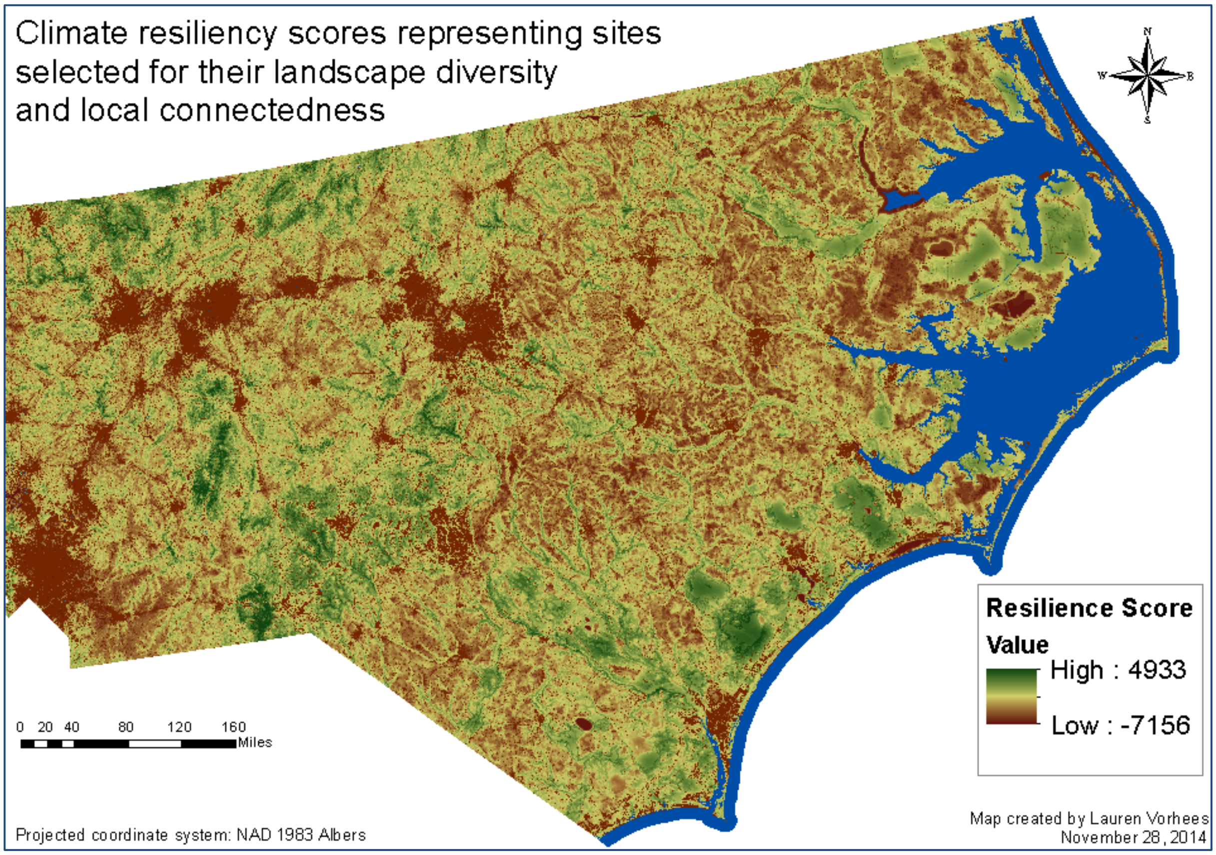

Figure A.11 – Spatial distribution of climate resiliency scores for ecosystems across North Carolina, created by the Nature Conservancy.