# Tick-Borne Disease Risk along the Appalachian Trail

by

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## Abstract

National Parks, created to protect natural and historic landmarks, and characterized by unique, preserved ecosystems, attract many visitors from around the world. These visitors, as well as employees, frequently engage in a variety of outdoor activities that allow for close contact with animal and plant diversity. As a result, they may experience greater exposure to ticks that transmit human pathogens and cause disease.

This paper assesses tick-borne disease risk in the National Park Service (NPS) units located along the Appalachian Trail: Delaware Water Gap National Recreation Area, Harpers Ferry National Historical Park, Chesapeake and Ohio Canal National Historical Park, Shenandoah National Park, the Blue Ridge Parkway, and Great Smoky Mountains National Park. It focuses on three tick vectors: *Ixodes scapularis*, the Black-legged tick or Deer tick, *Amblyomma americanum*, the Lone star tick, and *Dermacentor variabilis,* the American dog tick or Wood tick.

Since the distribution of tick vectors is related to environmental factors, land cover, landscape structure, and elevation were quantified for the national park service units and the surrounding residential areas to determine their similarity and the possibility for the transferability of risk estimates. Differences with the percentage of forested area and the amount of edge habitat were found to be statistically significant. As a result, data from tick sampling in the NPS units is needed to estimate disease risk. However, the current knowledge on the abundance, infection prevalence, and seasonal phenology of ticks along the Appalachian Trail is insufficient and outdated.

The true risk of tick-borne diseases in national parks is unknown, and likely under recognized. It is recommended that tick sampling as part of a larger tick-borne disease surveillance program be implemented in the national parks. As a starting point to further study, general tick habitat suitability was modeled for the NPS units along the Appalachian Trail based on land cover, elevation and moisture. Potential tick sampling sites were selected based on areas of high tick habitat suitability and high visitor use.

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## Introduction

National Parks, created to protect natural and historic landmarks, and characterized by unique, preserved ecosystems, attract many visitors from around the world. These visitors, as well as employees, frequently engage in a variety of outdoor activities that allow for close contact with animal and plant diversity. As a result, they may experience greater exposure to ticks that transmit human pathogens and cause disease. The most commonly reported tick-borne disease in the United States is Lyme disease, and over 30,000 cases were reported in 2010, with the majority occurring in the northeastern United States [1].

Unfortunately, in many national parks in the Eastern United States, the true risk of acquiring tick-borne diseases such as Lyme disease, Rocky Mountain Spotted Fever, Anaplasmosis, Tularemia, Ehrlichiosis, Southern Tick Associated Rash Illness, and Babesiosis is unknown. This is partially attributable to the challenges associated with assessing the true risk of tick-borne diseases outside of residential areas. Costly and time-intensive tick sampling measures are required to assess risk on public lands such as national parks.

The National Park Service (NPS) Office of Public Health and the Centers for Disease Control and Prevention (CDC) Division of Vector-borne Diseases are collaborating to assess tick-borne disease risk in the National Parks, with an initial focus on the NPS units located along the Appalachian Trail (AT). My research supports this project, by demonstrating a need for increased tick sampling and testing for pathogens within the NPS units, and providing sampling recommendations.

### Objectives

1) Summarize current knowledge on the abundance, infection prevalence, and seasonal phenology of ticks along the Appalachian Trail.
2) Define the environmental variables associated with tick distribution and disease risk.
3) Quantify and compare selected ecological drivers of risk for national park service units and the surrounding areas.

4) Model general tick habitat suitability for the national park units along the Appalachian Trail based on environmental variables.
5) Recommend tick sampling sites based on areas of high tick habitat suitability and high visitor use.

**Ticks and Tick-borne Diseases**

There are three primary ticks of public health importance along the Appalachian Trail [2]. *Ixodes scapularis*, the Black-legged tick or Deer tick, can transmit the etiological agents of Lyme Disease (*Borrelia burgdorferi*) [3], Anaplasmosis (*Anaplasma phagocytophilum*) [4, 5], and Babesiosis (*Babesia microti*) [6]. *Amblyomma americanum*, the Lone star tick, transmits the causative agents of Ehrlichiosis (*Ehrlichia chaffeensis and E. ewingii*) [5-7], Tularemia (*Francisella tularensis)* [8], and Southern Tick-Associated Rash Illness (STARI) [9, 10]. *Dermacentor variabilis,* the American dog tick or Wood tick carries the agents of Rocky Mountain Spotted Fever (*Rickettsia rickettsii*) [6, 11], Tularemia [8], and potentially Ehrlichiosis [4].

The general distribution of these tick species includes nearly all of the East Coast, and covers most of the Appalachian trail, according to the CDC's coarse geographic distribution maps [2] (Figure 1). However, incidence rates for the nationally notifiable diseases [1, 12] show variable disease prevalence within this range (Table 1). Lyme disease incidence is highest in states north of Maryland, with states to the south reporting more cases of Rocky Mountain Spotted Fever. Incidence rates for Ehrlichiosis caused by *E. chaffeensis,* Anaplasmosis and Tularemia remained low for the length of the trail [1]. Southern Tick-Associated Rash Illness and Babesiosis are not nationally notifiable diseases, so comparable data is not available.

**FIGURE 1: GEOGRAPHIC DISTRIBUTION OF TICKS ALONG THE EAST COAST**

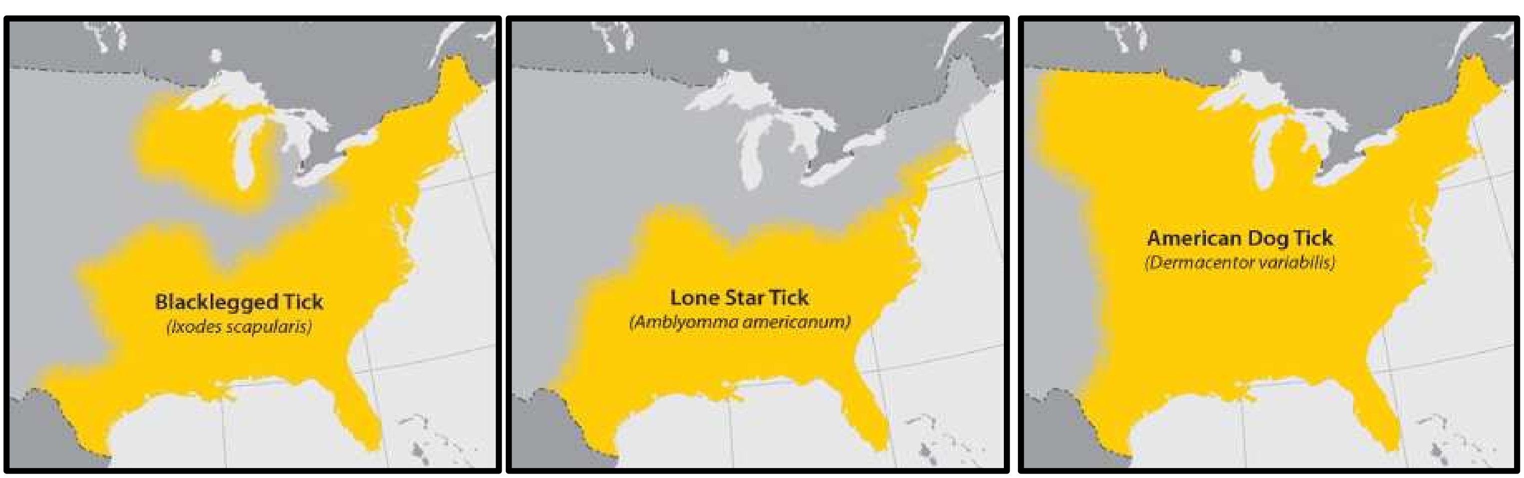


**TABLE 1: NOTIFIABLE TICK-BORNE DISEASE INCIDENCE RATES BY STATE (PER 100,000 PEOPLE)**

| | **Lyme disease** | | **Rocky Mountain Spotted Fever** | | **Ehrlichiosis** (*E. chaffeensis* only) | | **Anaplasmosis** | | **Tularemia** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **2009** | **2010** | **2009** | **2010** | **2009** | **2010** | **2009** | **2010** | **2009** | **2010** |
| Maine | 60.11 | 42.41 | 0.38 | 0.15 | 0.08 | 0.30 | 1.14 | 1.29 | 0.00 | 0.00 |
| New Hampshire | 75.68 | 62.64 | 0.08 | 0.08 | 0.30 | 0.23 | 1.37 | 1.51 | 0.68 | 0.08 |
| Vermont | 52.01 | 43.57 | 0.16 | 0.00 | 0.16 | 0.00 | 0.00 | 0.32 | 0.16 | 0.00 |
| Massachusetts | 61.85 | 36.09 | 0.11 | 0.00 | 0.14 | 0.00 | 1.52 | 0.00 | 0.06 | 0.05 |
| Connecticut | 78.58 | 55.83 | 0.00 | 0.00 | 0.00 | 0.00 | 0.63 | 1.22 | 0.03 | 0.00 |
| New York | 21.21 | 12.20 | 0.08 | 0.15 | 0.41 | 0.19 | 1.28 | 1.10 | 0.00 | 0.00 |
| New Jersey | 52.95 | 38.13 | 0.73 | 0.70 | 1.17 | 0.60 | 0.81 | 0.88 | 0.02 | 0.01 |
| Pennsylvania | 39.77 | 26.16 | 0.13 | 0.12 | 0.11 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 |
| Maryland | 26.02 | 20.41 | 0.71 | 0.86 | 0.59 | 0.39 | 0.02 | 0.26 | 0.02 | 0.00 |
| West Virginia | 7.88 | 7.03 | 2.92 | 0.00 | 0.06 | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 |
| Virginia | 8.98 | 11.56 | 0.68 | 1.84 | 0.68 | 0.99 | 0.04 | 0.15 | 0.00 | 0.01 |
| Tennessee | 0.16 | 0.10 | 0.03 | 4.92 | 0.02 | 0.91 | 0.00 | 0.17 | 0.06 | 0.05 |
| North Carolina | 0.23 | 0.22 | 2.77 | 3.05 | 0.57 | 1.06 | 0.03 | 0.30 | 0.01 | 0.03 |
| Georgia | 0.41 | 0.10 | 0.24 | 0.58 | 0.19 | 0.20 | 0.01 | 0.01 | 0.00 | 0.00 |

## Disease Interventions

Given the increasing number of tick-borne disease cases, tick and pathogen control are important public health concerns. Substantial research has focused on the efficacy of interventions that aim to prevent tick-borne diseases.

Some tick-borne disease interventions focus on modifying human behavior to reduce exposure or prevent transmission. Others aim to reduce tick density through area-wide application of chemical or biological agents, treatment of hosts with acaricides, reduction of tick hosts (primarily deer), or landscape management. Vaccinations and prophylactic antibiotic treatments can be used to lower the prevalence of infection in hosts or ticks, or prevent human cases of diseases [13].

The National Park Service management policy is not to intervene in natural biological or physical processes, and to preserve and maintain all resources, including ticks, for future generations. Exceptions are made if deemed necessary to protect human health. However, interventions should aim to minimize human changes to the environment [14]. Modifying human behavior requires the least modification to the environment and is the most compatible with the NPS mission.

Health risk messaging provides information to visitors about their risk of exposure to tick-borne pathogens, and encourages the use of personal protection measures. This can be implemented through increased informational signage at trailheads and visitor centers about ticks (Figure 2) [15], or educational campaigns to encourage individuals to wear appropriate clothing and footwear, perform tick checks, and shower frequently.

**FIGURE 2: TRAIL SIGN FOR LYME DISEASE PREVENTION**


Human behavior modifications can be done without detailed studies or tick sampling, however, there are challenges associated with risk messaging. Messages need to be designed so that they do not discourage outdoor activities by instilling fear, or overwhelm readers with too much information. Additionally, knowledge of Lyme disease and precautions does not always result in behaviors that promote disease prevention. While general knowledge of ticks nationwide is nearly universal and most people are aware of at least one disease prevention strategy, only 40-60% of people actually take any precautions [16, 17]. The strongest predictors for taking precautions include knowing someone with Lyme disease, and believing the disease is serious and difficult to cure [16, 17]. Increased visual cues as reminders, such as signage and employees modeling appropriate attire, may help to reinforce what visitors already know, and encourage them to use precautions [17].

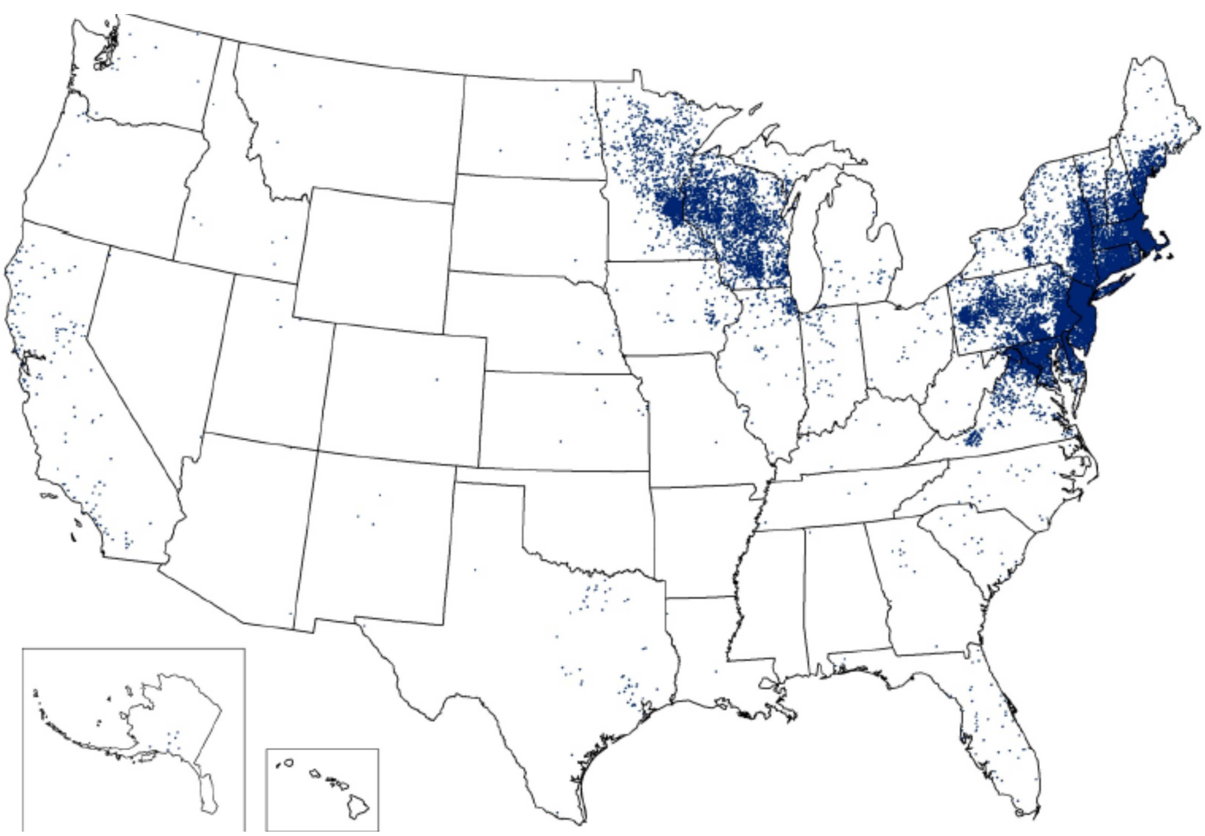
Interventions to reduce tick density or vaccinate and treat hosts are generally incompatible with the NPS mission. However, these interventions could potentially be targeted to small areas in the event of a severe disease outbreak. Prior knowledge of areas of known or likely high risk, and the seasonal timing of tick host seeking activity, could limit environmental modifications while providing benefits to human health.

## Models for Estimating Disease Risk

Estimating the risk of acquiring a tick-borne disease can be done with the use of models, and requires either data on disease cases (epidemiological) or tick presence and infection prevalence (acarological).

Health departments and government agencies frequently use epidemiological data on notifiable tick-borne diseases to identify high-risk areas. Cases reported by a patient's location of residence identify disease hotspots, typically at the county level, and drive passive surveillance systems. Below, a map of reported cases of Lyme disease based on the patient's county of residence shows that high risk areas are in the northeast and parts of the Midwest (Figure 3) [18].

**FIGURE 3: REPORTED CASES OF LYME DISEASE IN THE UNITED STATES IN 2010**



There are several significant disadvantages to the use of epidemiological data for examining tick-borne disease risk in the national parks. For diseases that are not nationally notifiable, such as STARI and Babesiosis, this epidemiological data may not be available. For the nationally notifiable diseases, standard surveillance systems do not capture infections acquired on recreational public lands such as national parks, where park visitors and employees are non-resident transient populations. If individuals acquire a tick-borne disease while visiting a national park to which they have traveled, it will most likely be detected when they visit a doctor after returning home. Since patient case reports often lack detailed travel histories, the case will be reported from the patient's county of residence.

Another major challenge of using epidemiological data is that risk from surrounding residential areas may not be transferable to the nearby national parks, despite their close proximity. Land within the national parks may be different as a result of varying land use and wildlife management policies. Moreover, national park visitors may experience a different risk because of greater exposure due to outdoor activities they are engaged in while visiting. It is also important that models are at scales appropriate for the interventions being considered. An understanding of risk at a finer scale than the county level is often required.

Studying risk on public lands requires acarological data. Obtaining this data is a costly and time-intensive process that involves sampling for ticks in the field and testing them in the laboratory for infections that can be transferred to humans [19]. Given these constraints, current acarological data is insufficient for the development of risk models in many areas.

Information on environmental variables can be used to supplement epidemiological and acarological data. Risk models have been developed over large landscapes for Tularemia [20], Lyme disease [21, 22], and Ehrlichiosis [23]. Sampling in small areas determines the environmental conditions associated with tick or pathogen presence, and then this information is extrapolated over a greater area using geographic information systems (GIS).

## Study Site

The Appalachian Trail (AT) is an ideal study site for examining tick-borne disease risk on public lands. Its 2,175 mile route is essentially a delineated transect of the eastern United States, passing through fourteen states and a wide variety of habitats and climates between Mount Katahdin, Maine and Springer Mountain, Georgia.

Land management along the trail is highly decentralized, divided among numerous federal and state agencies. This study will focus specifically on the six NPS units through which the Appalachian Trail passes: the Delaware Water Gap National Recreation Area, Chesapeake and Ohio Canal National Historical Park, Harpers Ferry National Historical Park, Shenandoah National Park, the Blue Ridge Parkway, and Great Smoky Mountains National Park (Figure 4).

High visitation rates and participation in activities that increase exposure to ticks suggests tick-borne diseases may pose a significant threat to visitors and employees along the AT. It is estimated that between 2 and 3 million visitors walk a portion of the Appalachian Trail each year, with 1,800-2,000 hikers attempting to hike its entirety in one season (thru-hikers)[24]. One survey of AT hikers found nearly a quarter reported tick bites and exposure [25].

Visitors to the NPS units that contain the Appalachian Trail have even higher visitation rates than the trail itself. Great Smoky Mountains National Park receives the most recreational visitors of any of the national parks in the United States. Popular activities that might result in a higher exposure to ticks are camping and wildlife viewing. In parks where a large percentage of visitors reported swimming, taking scenic drives, or visiting exhibits and museums, such as Delaware Water Gap, Blue Ridge Parkway, Great Smoky Mountains, and Harpers Ferry, risk might be lower. Table 2 summarizes the number of visitors and the most popular activities for each of the NPS units [26-32].

These visitors are not all from the immediate vicinity of the park. During March of 2004, visitors from 3,129 unique zip codes entered Shenandoah National Park, primarily from New York, Pennsylvania, Ohio, West Virginia, Virginia, Maryland, Washington DC, Delaware, and New Jersey [33]. Visitor surveys conducted in each of the NPS units show that visitors are traveling from all regions of the United States (Figure 5) [26-31]. This may mean that cases of tick-borne diseases acquired in national parks are being misreported to counties located around the country. Additionally, out-of-town visitors to national parks may be unaware of some preventative strategies and the appropriate time to use them, resulting in a greater risk.

The range of the Appalachian Trail includes the states with both the highest number of cases of Lyme disease and Rocky Mountain Spotted Fever in the United States [1]. Epidemiological data of Lyme disease cases reported for the counties along the Appalachian Trail shows that the highest rates of Lyme disease occur in New York, Connecticut, and New Jersey, and incidence rates have increased from 1992 to 2006 (Figure 6) (appendix II). This is a starting point for estimating disease risk along the trail. The availability and quality of state data at the county level for the other nationally notifiable diseases varied.

**TABLE 2: NPS UNIT VISITATION AND ACTIVITY SUMMARY**

| | Annual Visitors (2010) | Most Popular Activities (% of visitors reporting participation) |
|---|---|---|
| Delaware Water Gap National Recreation Area | 5,285,761 | 1. Swimming (56%)<br>2. Viewing scenery/river views/waterfalls (36%)<br>3. Hiking/walking (36%) |
| Harpers Ferry National Historical Park | 268,822 | 1. Hiking/walking (82%)<br>2. Viewing exhibits/museums (74%)<br>3. Shopping at shops/restaurants (62%) |
| Chesapeake and Ohio Canal National Historical Park | 4,111,238 | 1. Hiking/walking/jogging (64%)<br>2. Viewing Great Falls (28%)<br>3. Bicycling (22%) |
| Shenandoah National Park | 1,253,386 | 1. Scenic drive and overlooks (87%)*<br>2. Enjoying solitude/natural quiet (75%)*<br>3. Viewing wildlife and plants (72%)* |
| Blue Ridge Parkway | 14,517,118 | 1. Scenic drive (89%)<br>2. Taking photographs/painting/drawing (52%)<br>3. Hiking/walking (44%) |
| Great Smoky Mountains National Park | 9,463,538 | 1. Scenic drive (95%)<br>2. Viewing wildlife and plants (69%)<br>3. Hiking/walking (62%) |

*In Shenandoah National Park, visitors were asked to rate the importance of selected reasons for visiting. This is different than the survey question in the other NPS units, which asked visitors the activities they participated in during their visit.

**FIGURE 4: MAP OF THE STUDY SITE: NATIONAL PARK SERVICE UNITS ALONG THE APPALACHIAN TRAIL**

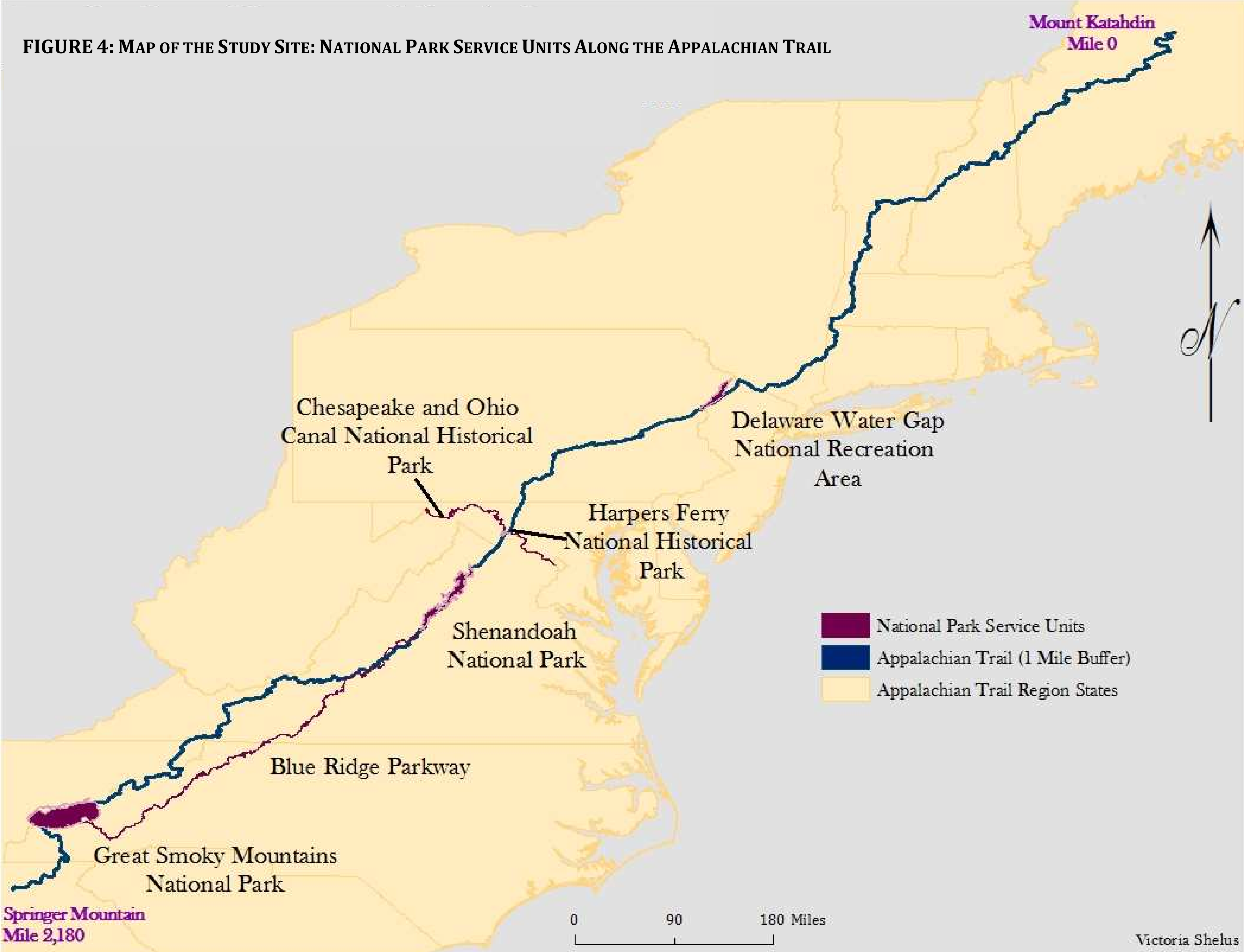


**FIGURE 5: MAP OF NATIONAL PARK SERVICE UNIT VISITORS BY STATE OF RESIDENCE**

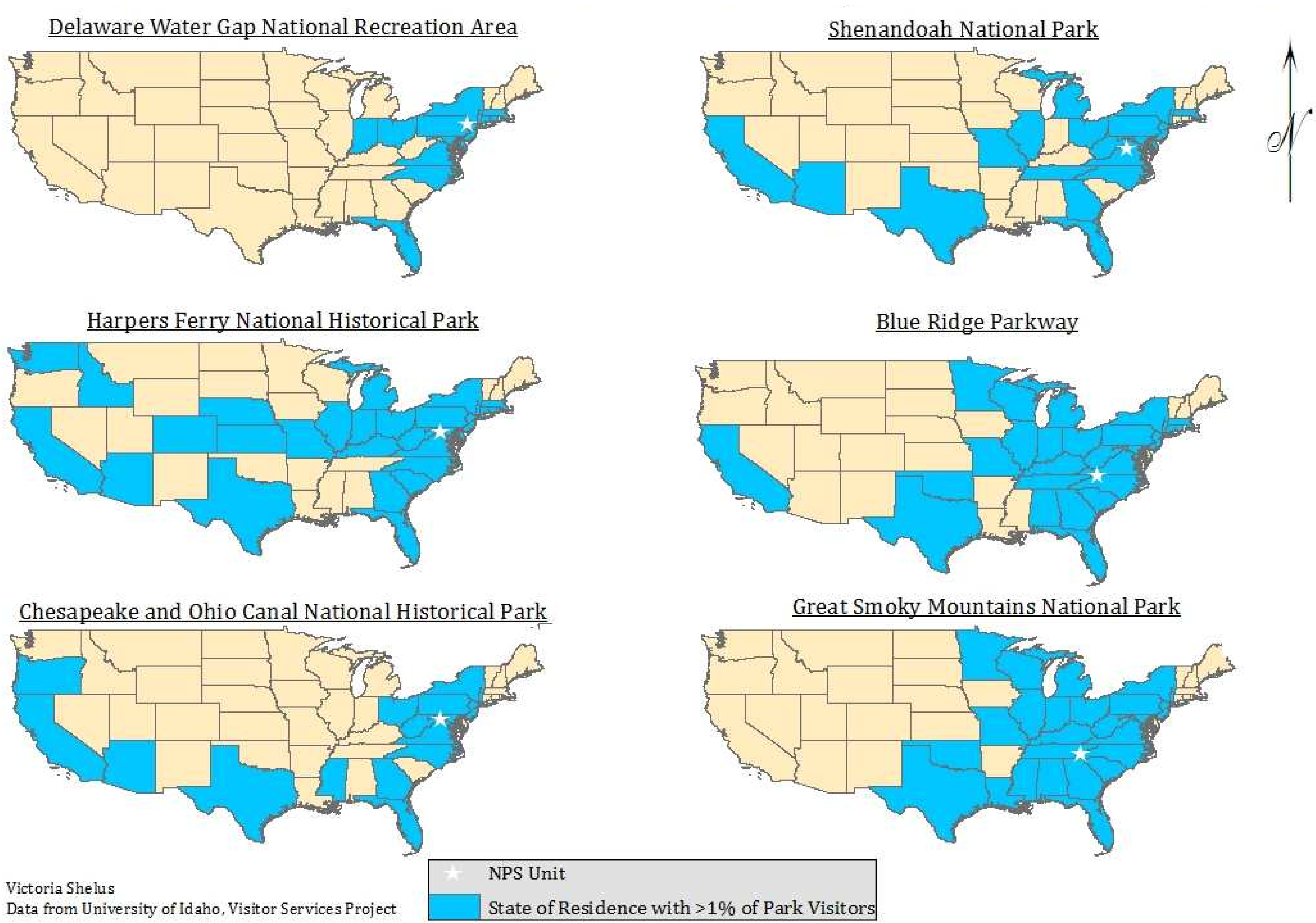
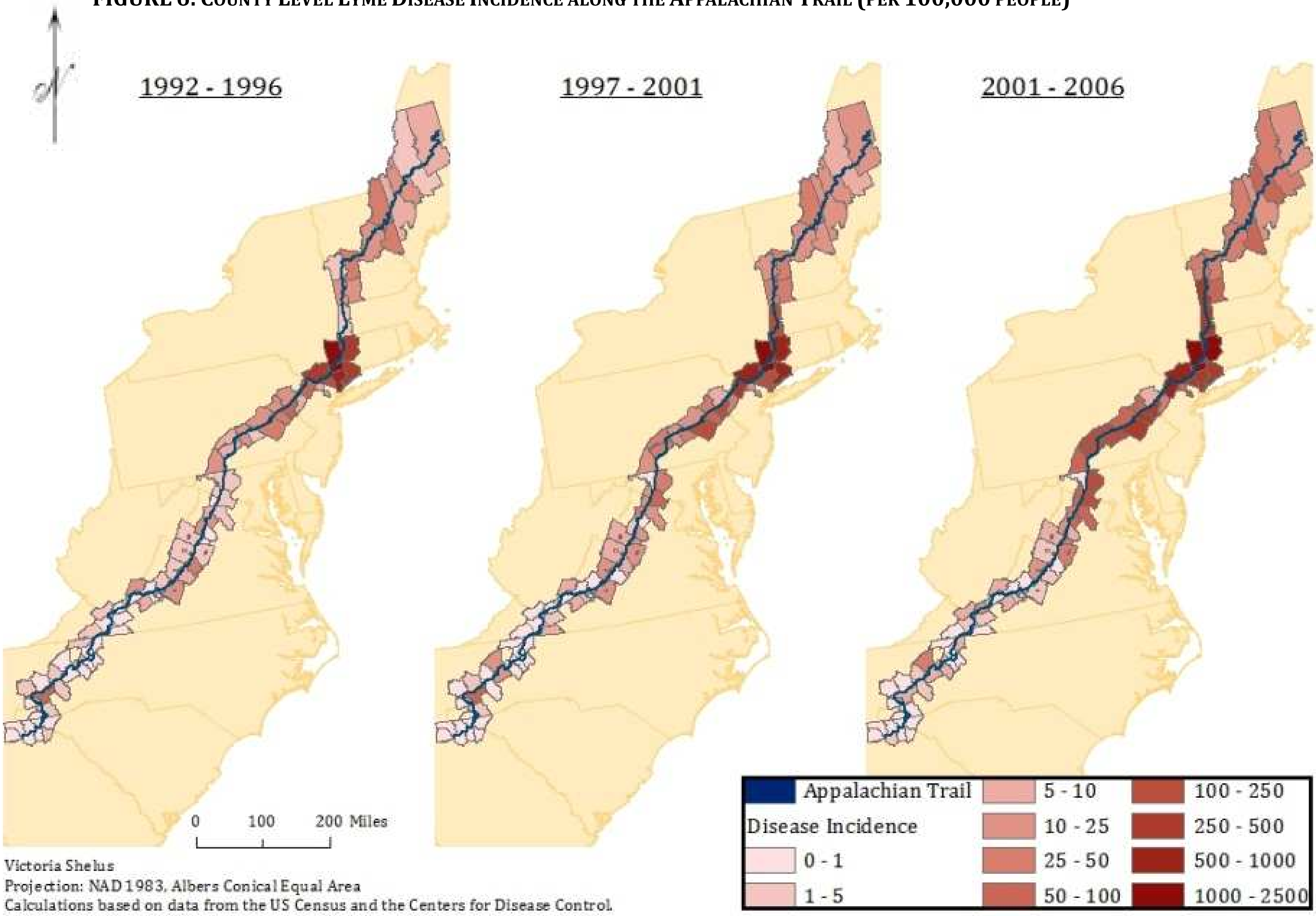


**FIGURE 6: COUNTY LEVEL LYME DISEASE INCIDENCE ALONG THE APPALACHIAN TRAIL (PER 100,000 PEOPLE)**




Victoria Shelus
Projection: NAD 1983, Albers Conical Equal Area
Calculations based on data from the US Census and the Centers for Disease Control.

# Methods

## Literature review

A literature review was conducted with Web of Science as the main reference index. Scientific articles were obtained that pertained to six major categories: tick life cycle and ecology; the abundance, infection prevalence, and seasonal phenology of ticks from field sampling within the national parks or the surrounding counties; environmental variables and their correlation with tick distribution and disease risk; GIS and risk modeling methods; tick sampling techniques and methods; and recommendations for tick control and disease prevention. Given the broad nature of this research, initial searches were for any articles including the scientific names of the three focus tick species: *Ixodes scapularis, Amblyomma americanum,* and *Dermacentor variabilis.* Additional references were obtained as a result of citation in a relevant article.

## Geospatial analysis

Geospatial analysis was used to quantify differences between the NPS units and the surrounding counties, model general tick habitat suitability, and recommend tick sampling sites. Based on the findings of the literature review with regards to ecological drivers of risk, environmental variables chosen for analysis were land cover, elevation, fragmentation, and moisture.

Layers for geospatial analysis and their sources are summarized in Table 3. While land cover and elevation were directly derived from the National Land Cover Dataset and the National Elevation Dataset respectively, fragmentation and moisture were calculated. Fragmentation was quantified as the average meters per hectare of natural-converted edge using the contrast-weighted edge density metric in Fragstats, a spatial pattern analysis program. Moisture was calculated from the wetness band of a tasseled cap transformation performed on Landsat 5 TM images (image data appendix iii). All layers were projected into Albers Conical Equal Area with the North American 1983 datum. Satellite images were radiometrically corrected[34], and resampling required on any layer was done with cubic convolution.

**Table 3: GIS Layers for Analysis**

| | GIS Layers | Agency | Means of Data Attainment |
|---|---|---|---|
| Land Cover | National Land Cover Database (2006)[35] | Multi-Resolution Land Characteristics Consortium (MRLC) | http://www.mrlc.gov/nlcd2006.php |
| Elevation | National Elevation Dataset (1 arc second)[36] | U.S. Geological Survey | Seamless Viewer http://seamless.usgs.gov/website/seamless/viewer.htm |
| Satellite Images | Landsat 5 TM Images | U.S. Geological Survey | Earth Explorer https://earthexplorer.usgs.gov |
| Appalachian Trail Layers | Appalachian Trail, States, Counties [37] | Appalachian National Scenic Trail Office | Personal Communication with Casey Reese |
| Individual National Park Unit Layers | Boundaries, Trails, Rivers and Lakes, Roads, Recreation Areas, Geology, Forest/Vegetation Cover | National Park Service, U.S. Department of the Interior | Integrated Resource Management Application Portal https://irma.nps.gov/App/Portal |

Land cover, elevation, and fragmentation were quantified for each of the National Park Service units and the surrounding counties. Counties were included in the analysis if they contained or bordered any portion of the NPS unit. Two-tailed t-tests were used to determine if differences between the NPS units and the surrounding counties were statistically significant.

For land cover, the area and percentage classified as each of the 16 National Land Cover Dataset classes was calculated, however most analysis focuses on the percentage of forested land. Land cover classes were also compared between the NPS units and the surrounding countries based on the natural or converted categories derived from the NPS land cover metrics program [35]. Natural classes include open water, perennial ice/snow, barren land (rock/sand/clay), deciduous forest, evergreen forest, mixed forest, grassland/herbaceous, woody wetlands, and emergent herbaceous wetlands. Converted classes are developed (open space, low intensity, medium intensity, and high intensity), pasture/hay, and cultivated crops.

Geospatial layers chosen to create the map of tick habitat and sampling site suitability include variables that influence human exposure because of high use (trails and points of interest), and variables that predict tick habitat suitability or are known to correlate with tick density and disease risk (land cover, elevation, and moisture). Points of interest varied by park, but were primarily visitor centers, campgrounds, picnic areas, and vistas. The rationale for the inclusion of each variable, and the general areas considered suitable for each layer, are summarized in Table 4.

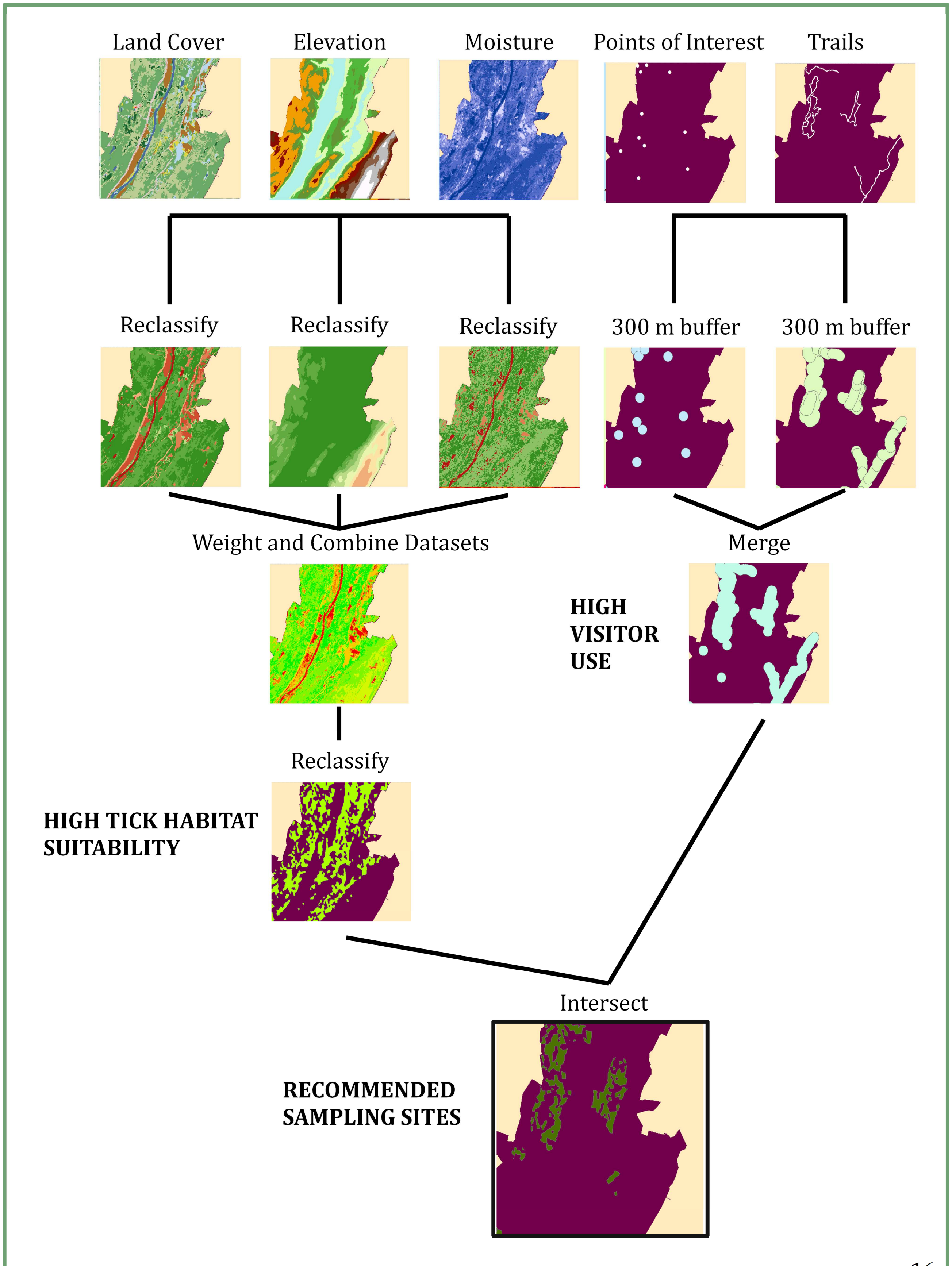
**TABLE 4: RATIONALE FOR ENVIRONMENTAL VARIABLES INCLUDED IN TICK HABITAT AND SAMPLING SUITABILITY MAP**

| | Rationale | Suitable Area |
|---|---|---|
| Elevation | Elevation is a proxy for temperature, and temperature has been found to be predictive of tick presence, Lyme disease incidence, and the fitness of pathogens [22, 36-38] [39, 40]. | Lower elevations with warmer temperatures and fewer temperature extremes. |
| Land Cover | The presence of forests is the most consistent association with Lyme disease risk, particularly mixed deciduous forests [41-44] | High suitability: Forests<br>Medium suitability: Grasslands/Herbaceous<br>Low suitability: Open water, wetlands, developed, barren land, agriculture |
| Wetness | Ticks are highly sensitive to moisture and humidity [41, 45]. Wetness, derived from the Tasseled cap transformation on satellite images, is a proxy for soil and canopy moisture. | Intermediate values, between open water and extremely dry areas. |
| Trails | Most exposure will occur on designated trails, not in dense, more isolated forest. Sampling should be done in areas that reflect likely exposure. | Within 300 meters of the center of a trail. |
| Recreation | Points of interest, as identified by the national parks, represent areas where visitor use and exposure could be the greatest. | Within a 300 meter buffer around points of interest. |

The geospatial methods for determining tick sampling sites are displayed in Figure 7. Categories within the land cover, elevation, and moisture layers were reclassified on a scale of 1 to 10, with 1 representing conditions highly unsuitable for tick survival, and 10 being highly suitable conditions (reclassification values in appendix iii). These were combined into one dataset to produce a suitability map, with land cover weighted more heavily (40%), than elevation and moisture (30% each) because it has consistently been shown to be the strongest predictor of disease risk [36]. Areas receiving a high combined score were extracted to create a layer representing those areas with the highest tick habitat suitability in the NPS unit. In Harpers Ferry National Historical Park, high scores were 8 through 10, in Shenandoah and Great Smoky Mountains National Parks high scores were 9 and 10, and in the Delaware Water Gap National Recreation Area a high score was 10 only. These differences represent an effort to limit the recommended sampling areas to feasible study sites as much as possible. Areas within 300 meters of a trail or point of interest were considered areas of high visitor use. Recommended sampling sites were derived from areas with both high tick habitat suitability and high visitor use.

Maps of tick habitat suitability and recommended sampling sites were created for the Delaware Water Gap National Recreation Area, Harpers Ferry National Historical Park, Shenandoah National Park, and the Great Smoky Mountains National Park. Chesapeake and Ohio Canal National Historical Park and Blue Ridge Parkway were excluded because of their extremely close proximity to one or more NPS unit(s) where sampling sites were recommended.

**FIGURE 7: GEOSPATIAL METHODS FOR DETERMINING TICK SAMPLING SITES BASED ON HABITAT SUITABILITY AND VISITOR USE**



## Results

### Tick Distribution

The most recent acarological data on tick distribution and infection prevalence for the national parks located along the AT are between 10 and 20 years old. While *I. scapularis* and *D. variabilis* are known to be abundant in the Delaware Water Gap National Recreation Area [37] and Great Smoky Mountains National Park [43] respectively, huge knowledge gaps exist for the other ticks and NPS units (Table 5). While there is some research to indicate low tick abundance in areas due to environmental conditions, particularly elevation, the majority of information remains unknown. In this category, tick species were documented within the region, but no published studies could be found for the national park unit or the surrounding counties. Only one study tested ticks to determine infection prevalence. This is necessary for accurate disease risk predictions because the presence of vectors does not imply the presence of pathogens.

**TABLE 5: EXPECTED TICK ABUNDANCE WITHIN NPS UNITS**

| | ***Ixodes scapularis*** | ***Amblyomma americanum*** | ***Dermacentor variabilis*** |
|---|---|---|---|
| **Delaware Water Gap National Recreation Area** | **Highly Abundant[37]**<br><br>(34% infected with *B. burgdorferi)* | Abundance unknown [38, 39] | Abundance unknown [38, 39] |
| **Harpers Ferry and Chesapeake and Ohio Canal National Historic Parks** | Likely low [21, 40] | Abundance unknown [38] | Abundance unknown [38] |
| **Shenandoah National Park and the Blue Ridge Parkway** | Likely low [21, 41] | Abundance unknown [38] | Abundance unknown [38, 39] |
| **Great Smoky Mountains National Park** | Likely low [21, 41]<br><br>(Not expected at the high elevation) | Likely low [42]<br><br>(Abundant in TN and NC but low in Blue Ridge Mountain Ecosystem) | **Abundant [43]**<br><br>(Based on tick surveys and raccoon trapping) |

## Tick Phenology

Knowledge of tick phenology (the timing of host-seeking activity) is used to determine when humans are most at risk for tick bites and exposure to tick-borne pathogens. This information can be used to determine when to implement interventions so they will be the most effective. Not enough studies currently exist to determine if there are slight differences in timing between National Park Service units along the Appalachian Trail, but suggest that for the life stages of ticks most likely to bite humans and transmit disease (*I. scapularis* nymphs, *A. americanum* nymphs and adults*, and D. variabilis* adults) the greatest risk is between April and July (Table 6) [37, 44-49]. This phenology data is primarily from studies conducted in the 1980s and 90s and may need updating if tick activity timing responds to changing climatic factors similar to tick range and distribution [22, 50].

**TABLE 6: PHENOLOGY SUMMARY OF TICKS AND LIFE STAGES ALONG THE APPALACHIAN TRAIL**

| Tick species and life stage | States sampled | Months active | Peak abundance |
|---|---|---|---|
| *Ixodes scapularis* nymphs | Massachusetts [44, 45], New York [46, 47], New Jersey [37] | April-September | May - July |
| *Amblyomma americanum* nymphs | Tennessee [48], Georgia [51], Mississippi [52] | April – September | April - June |
| *Amblyomma americanum* adults | Tennessee [48], Georgia [51], Mississippi [52] | March – August | April - May |
| *Dermacentor variabilis* adults | New York [46], Virginia [49], Georgia [53], Kentucky [54] | Late March – early September | April - June |

## Ecological Drivers of Risk

The distribution of tick vectors is related to environmental factors. *Ixodes scapularis* abundance and infection prevalence is associated with **climate**, specifically precipitation, temperature, and humidity; **landscape characteristics** such as vegetation, soil type, and forest fragmentation; and **host diversity and abundance.** More limited research focusing on the relationship between environmental variables and *Amblyomma americanum* and *Dermacentor variabilis* is available.

*Climate*

Strong connections can be made between climate and tick and disease ecology. Ticks are highly sensitive to changes in their microclimate [55], with humidity [56, 57], temperature [22, 58], and precipitation [58, 59] affecting tick survival and distribution. Additionally, the fitness of pathogens carried by ticks and transmitted to humans is related to seasonal factors [60, 61]. The geographic ranges of ticks are expanding [62], and changing climatic conditions have been shown to correlate with reported changes in tick density and occurrence [50]. Elevation will be used as a proxy for microclimate in subsequent analysis.

*Landscape Characteristics*

Land cover can influence vector distribution and abundance, and is a strong determinant of risk. Lyme disease is known to vary with vegetation type and cover [36], and has been correllated with habitat fragmentation [63]. The most consistent land cover predictor of *I. scapularis* is the presence of forests, particularly deciduous or mixed forests with a layer of leaf litter [36]. There is also a positive correlation between *I. scapularis* distribution and sandy, micaceous, and fine-loamy soils [64, 65]. Public lands, with undisturbed forests and more accumulated leaf litter, may have a higher risk than surrounding suburban or urban areas where forests have undergone development.

Several studies have found increased tick density and infection prevalence in fragmented landscapes, with higher risk in small, isolated forest patches [66-68] and along forest edges [63, 69]. Extremely small forest patches however, may have low risk because of frequent local tick extinctions [70]. Explanations for the relationship between fragmented landscapes and exposure to *B. burgdorferi* include a loss of species diversity in fragmented areas, preference by white-tailed deer for foraging in edge habitat, and high human use in these areas. This last theory proposes that forest edges may have a higher risk because of human behaviors and increased recreational use compared with areas deep within the forest, not because of any inherent differences in tick abundance or infection prevalence that may be caused by environmental factors [71].

*Host Diversity and Abundance*

Disease risk is influenced by both the diversity and abundance of host species. Ticks require a blood meal to molt to the next stage of their life, so a sufficient number of hosts must be present to complete the full life cycle. Larval and nymphal ixodid ticks typically feed on small to medium sized mammals (mice, rats, chipmunks, squirrels, opossums, shrews, raccoons) and birds, while adult ticks typically feed and mate on larger animals, especially deer [72, 73].

These host species vary in their potential as reservoirs. Species are effective reservoirs if while carrying the pathogen, a high proportion of ticks feeding on them become and remain infected after molting. *Peromyscus leucopus*, the white-footed mouse, is a highly effective reservoir host for *B. burgdorferi.* Many small forest patches have low vertebrate diversity because conditions for survival are not ideal. However, this environment allows the generalist white-footed mouse to thrive, and it is often the dominant host species in fragmented landscapes [74]. In areas of greater diversity, other vertebrates, with lower reservoir competence, can serve as hosts, and dilute infection prevalence [75]. If national parks have greater mammal diversity, then rates of Lyme disease may actually be lower than in residential areas. Less research has been conducted on the reservoir competence of mammals for other tick-borne pathogens, and the relationship between diversity and disease risk.

The increased risk in forest edges and fragmented landscapes may be a result of increased deer activity. White-tailed deer, *Odocoileus virginianus* thrive in forest edge habitat, foraging on the small shrubs and grasses that are found there. In many regions *O. virginianus* is the primary host for adult ticks and an important amplifying host. A positive correlation between deer density and tick abundance has been observed at multiple spatial scales [76, 77], and deer density reduction or removal programs have been shown to reduce tick density [78, 79]. This suggests that high tick densities may exist in national parks where there are large deer populations due to protection from hunting and ample habitat. In some cases, however the presence of too many deer and elk may alter the environment so that is unsuitable for tick survival. In Rocky Mountain National Park, low tick abundance was observed in areas heavily browsed by deer and elk. It was proposed that a huge growth in elk populations and the subsequent overgrazing of vegetation may have led to a suppression in rodent populations and a decrease in tick abundance [80].

### National Park Service Units Landscape Characteristics

While their close proximity suggests that epidemiological data from the counties surrounding the national parks could be used to estimate disease risk within the parks, these estimates may be inaccurate as a result of dissimilar environmental conditions. Of the ecological drivers of risk identified from the literature review, five in particular would be expected to differ between the national parks and the surrounding counties: deer density, vertebrate density, land cover, landscape structure (fragmentation), and elevation (Table 7).

**TABLE 7: ECOLOGICAL DRIVERS OF RISK EXPECTED TO VARY BETWEEN NATIONAL PARK SERVICE UNITS AND THE SURROUNDING COUNTIES**

| Ecological Characteristic | Risk Association | Expected Greater Risk |
|---|---|---|
| Deer Density | High density | National Parks |
| Vertebrate Diversity | Low diversity, high white-footed mouse abundance | Residential Areas |
| Land Cover | Deciduous or mixed forests with leaf litter | National Parks |
| Landscape Structure | Fragmented | Residential Areas |
| Elevation | Lower elevations | Residential Areas |

Data on deer and vertebrate density could not be found on a fine enough scale to allow for differentiation between the parks and the surrounding counties. Measures of land cover, landscape structure, and elevation were quantified for the national parks and the surrounding counties, and are summarized in Table 8. There were statistically significant differences ($p<0.05$) between the national park service units and the surrounding counties for the percentage of forested area ($p = 0.00004$) and meters per hectare of edge habitat ($p= 0.043$), but not average elevation ($p = 0.171$).

**TABLE 8: COMPARISON OF LANDSCAPE CHARACTERISTICS BETWEEN THE NPS UNITS AND THE SURROUNDING COUNTIES**

| | Forested Area (%) | | Fragmentation (meters per hectare of natural-converted edge) | | Average Elevation (m) | |
|---|---|---|---|---|---|---|
| | Park | Counties | Park | Counties | Park | Counties |
| Delaware Water Gap National Recreation Area | 78.1 | 24.7 | 34.5 | 48.4 | 224 | 293 |
| Harpers Ferry National Historical Park | 66.4 | 15.4 | 33.7 | 47.7 | 191 | 172 |
| Chesapeake and Ohio Canal National Historical Park | 68.1 | 35.5 | 48.4 | 50.3 | 123 | 218 |
| Shenandoah National Park | 97.3 | 54.7 | 13.1 | 44.5 | 666 | 394 |
| Blue Ridge Parkway | 73.9 | 35.6 | 58.9 | 47.7 | 954 | 645 |
| Great Smoky Mountains National Park | 90.9 | 51.6 | 5.1 | 46.5 | 1005 | 644 |

The percentage of area classified as forests was higher in all of the NPS units compared with the surrounding area. The differences in percent forest cover ranged from 32.6% (Chesapeake and Ohio Canal NHP) to 53.4% (Delaware Water Gap NRA). Detailed, park-specific information on the land classification differences between the national parks and the surrounding counties can be found in the appendix. Overall, there was more forested area within the NPS units, compared with larger areas classified as developed, agriculture, and wetlands in the surrounding counties.

Landscape level fragmentation is higher outside of the parks, evidenced by more meters per hectare of natural-converted edge in the surrounding counties than all of their nearby NPS units. The greatest difference was Great Smoky Mountains National park, where edge habitat increased from 5.1 to 46.5 meters per hectare after leaving the national park. Blue Ridge Parkway was the only NPS unit to have greater fragmentation than the surrounding area. Given its unique status as a scenic parkway running through a mountainous region, this high level of fragmentation is expected. However, it was excluded from statistical analysis for that reason.

The difference in elevation varied between NPS units. Elevation was greater in the national parks for Harpers Ferry National Historical Park, Shenandoah National Park, the Blue Ridge Parkway, and the Great Smoky Mountains National Park. However, elevation was greater in the counties surrounding Delaware Water Gap National Recreation Area and Chesapeake and Ohio Canal National Historical Park than in the parks themselves.

**Tick Habitat and Sampling Site Suitability Analysis**

The recommended sampling sites based on tick habitat suitability and areas of high visitor use for Delaware Water Gap National Recreation Area, Harpers Ferry National Historical Park, Shenandoah National Park, and the Great Smoky Mountains National Park are shown in the next section.

**FIGURE 8: TICK HABITAT SUITABILITY IN DELAWARE WATER GAP NATIONAL RECREATION AREA**

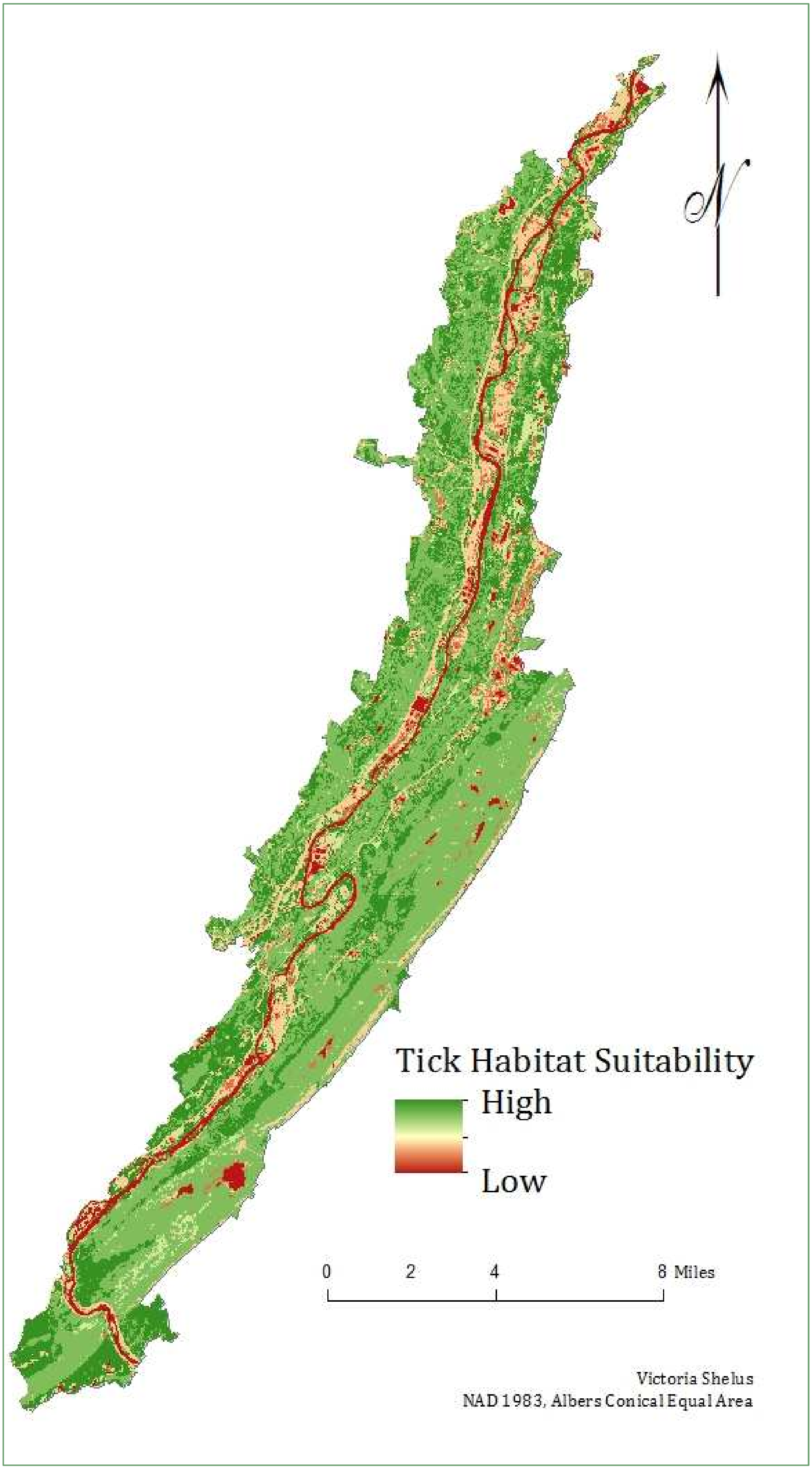


**FIGURE 9: RECOMMENDED SAMPLING AREAS IN DELAWARE WATER GAP NATIONAL RECREATION AREA**

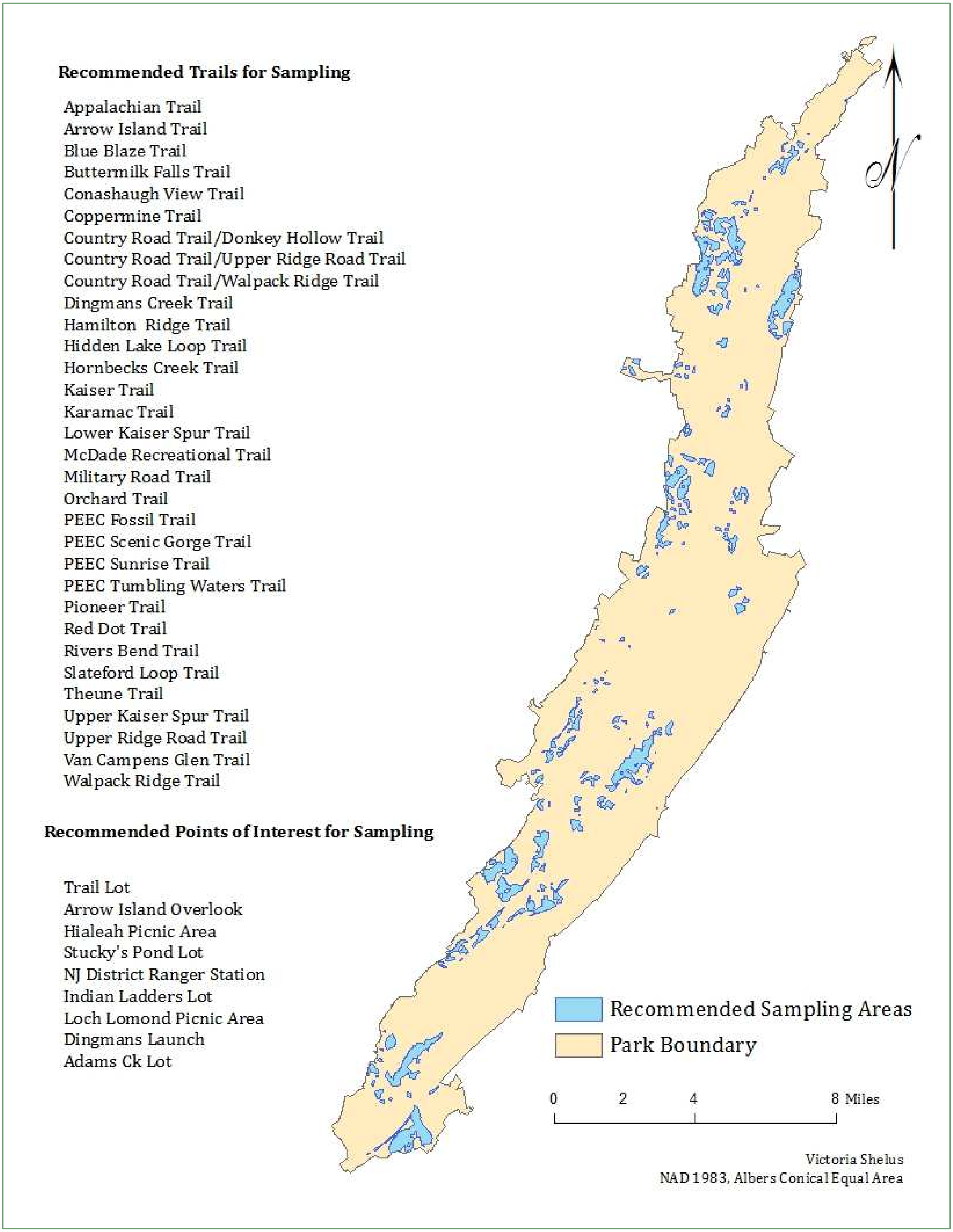


**FIGURE 10: TICK HABITAT SUITABILITY IN HARPERS FERRY NATIONAL HISTORICAL PARK**

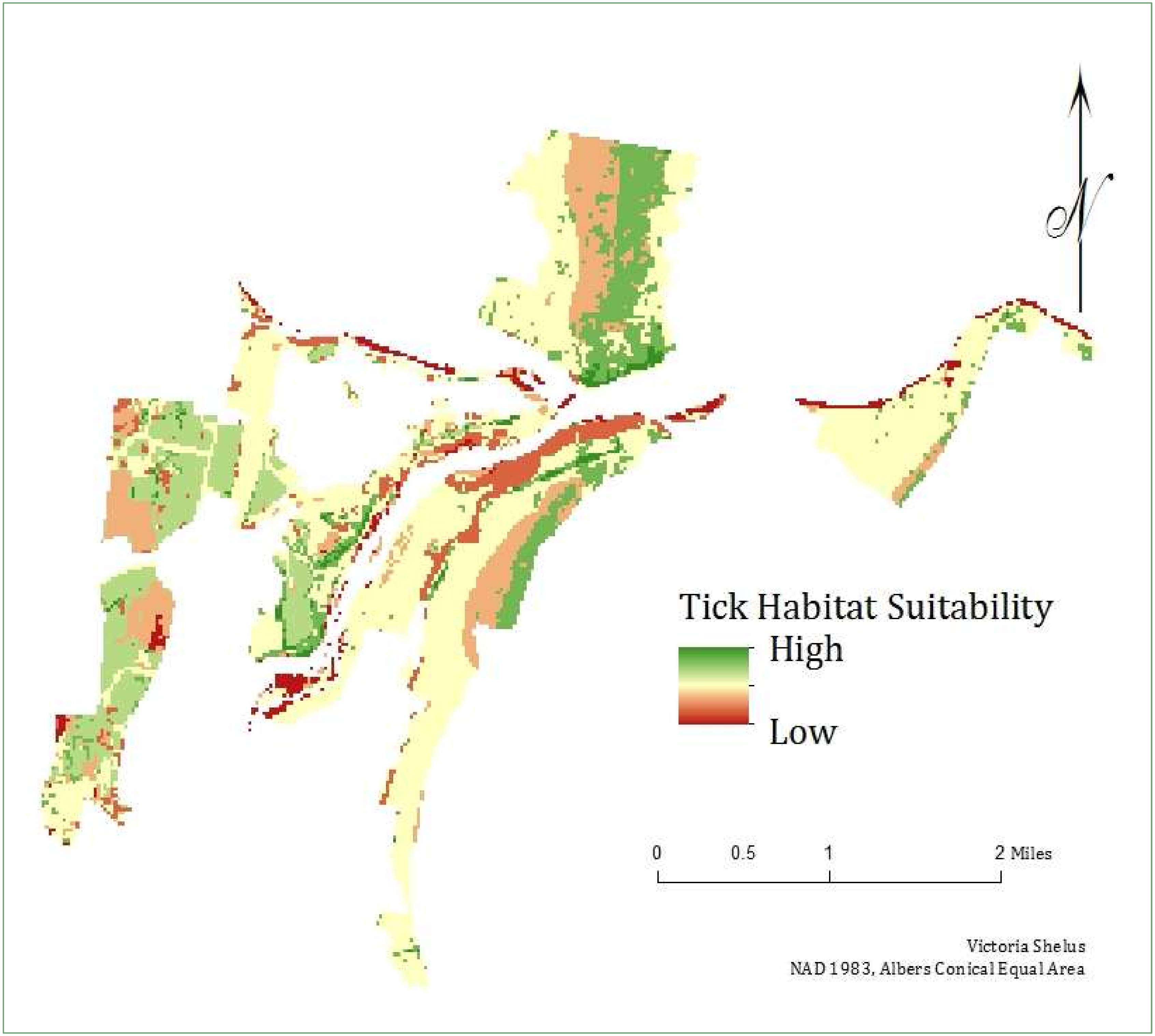


**FIGURE 11: RECOMMENDED SAMPLING AREAS IN HARPERS FERRY NATIONAL HISTORICAL PARK**

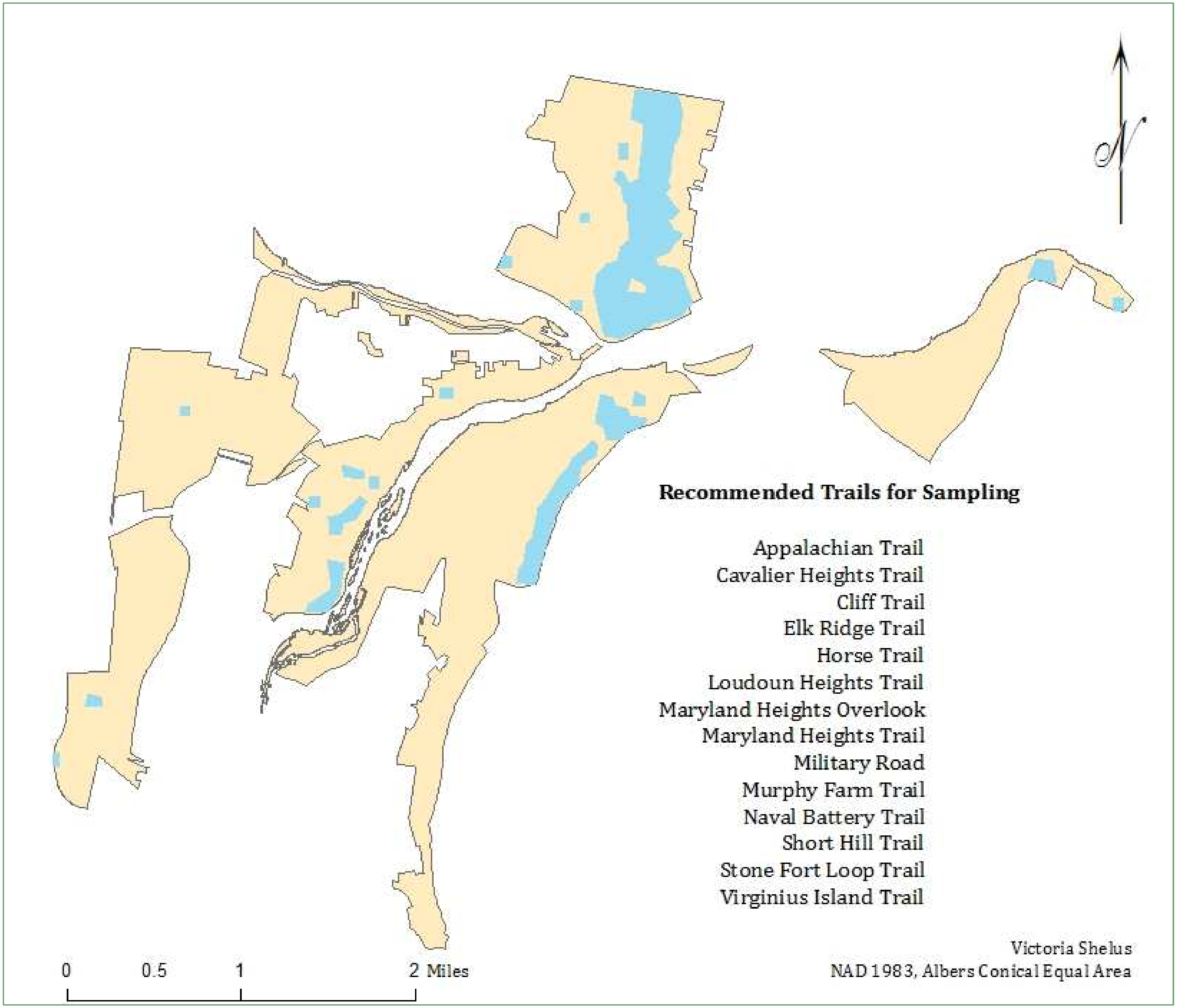


**FIGURE 12: TICK HABITAT SUITABILITY IN SHENANDOAH NATIONAL PARK**

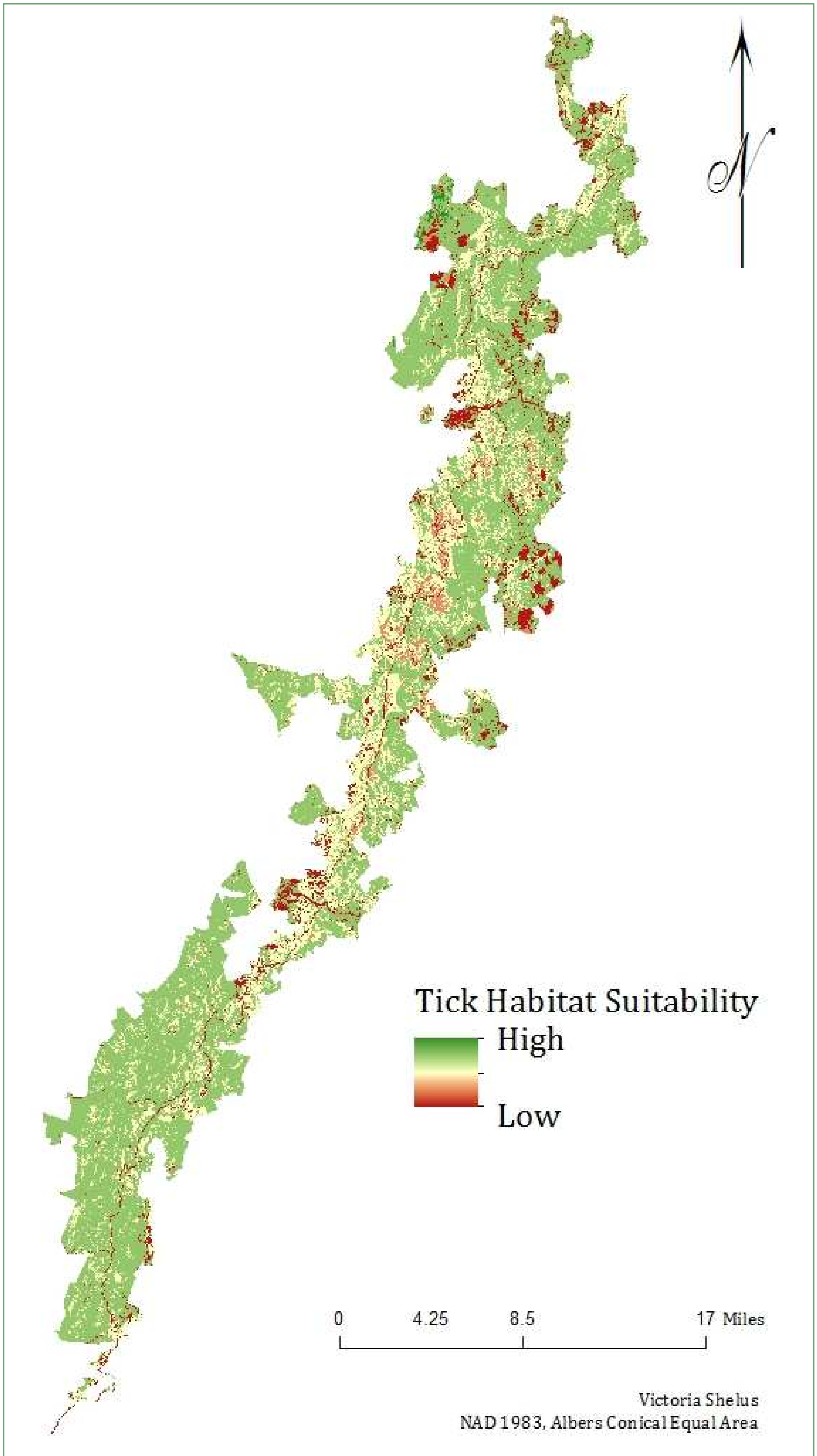


**FIGURE 13: RECOMMENDED SAMPLING AREAS IN SHENANDOAH NATIONAL PARK**

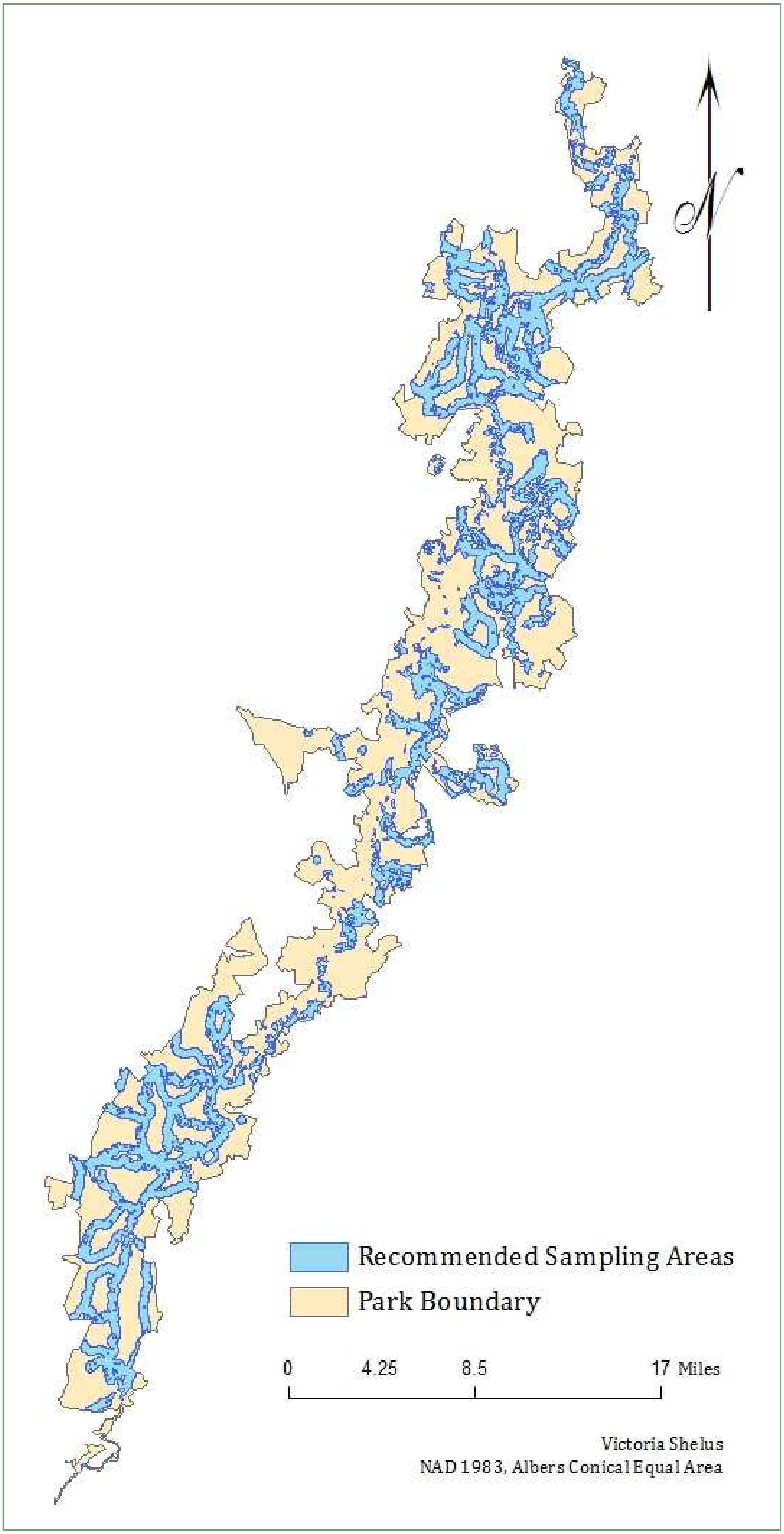


**TABLE 9: RECOMMENDED SAMPLING TRAILS AND VISTAS IN SHENANDOAH NATIONAL PARK**

| Recommended Trails for Sampling in Shenandoah |
| --- |
| |
| Appalachian Trail |
| Austin Mountain Trail |
| Beahms Gap Loop Trail |
| Bearfence Hut Trail |
| Beecher Ridge Trail |
| Big Devils Stairs Trail |
| Big Run Loop and Portal Trail |
| Blackrock Hut Trail |
| Bluff Trail |
| Broad Hollow Trail |
| Brown Mountain Trail |
| Browntown Trail |
| Buck Hollow Trail |
| Buck Ridge Trail |
| Camp Hoover Trail |
| Cat Knob Trail |
| Catlett Spur and Mountain Trail |
| Cave/Falls Spur Trail |
| Cedar Run Trail |
| Chimney Rock Spur Trail |
| Compton Peak Trail (East and West) |
| Conway River Trail |
| Corbin Hollow and Mountain Trail |
| Crusher Ridge Trail |
| Dark Hollow Falls Trail |
| Devils Ditch Hunter Access Trail |
| Dickey Ridge Trail |
| Doyles River Trail |
| Dundo Group Campground Trail |
| Eaton Hollow Trail |
| Elkwallow Trail |
| Entry Run Trail |
| Firing Range Trail |
| Five Tents Trail |
| Fork Mountain Trail |
| Fox Hollow Trail |
| Frazier Discovery Trail |
| Frazier Discovery Trail Access |
| Furnace Mountain Summit Trail |
| Gap Run Trail |
| Gods Area Bottom Trail |
| Gravel Springs Hut Trail |
| Graves Mill Trail |
| Hannah Run Trail |
| Harris Hollow Trail |
| Hazel Mountain Trail |
| Hazel River Trail |
| Heiskell Hollow Trail |
| Hemlock Run Trail |
| Hickerson Hollow Trail |
| Hightop Hut Trail |
| Hogback Spur Trail |
| Hull School Trail |
| Indian Run Trail |
| Jenkins Gap Trail |
| Jeremys Run Lower Trail |
| Jones Mountain Trail |
| Jones Run Trail |
| Jordan River Trail |
| Knob Mountain Trail |
| Laurel Prong Trail |
| Leading Ridge Trail |
| Lewis Peak Trail |
| Lewis Run Horse Trail |
| Lewis Spring Falls Trail |
| Little Devils Stairs Trail |
| Loft Mountain Campground Trail |
| Madison Run Spur Trail |
| Mathews Arm Trail |
| McCormick Gap Horse Trail |
| McDaniel Hollow Trail |
| Meadow School Trail |
| Meadow Spring Trail |
| Mill Prong Trail |
| Mt Marshall Trail |
| Neighbor Mountain Trail |
| NF Moormans River Trail |
| Nicholson Hollow Trail |
| Onemile Run Trail |
| Overall Run Trail |
| Paine Run Trail |
| Pass Mountain Trail |
| Patterson Ridge Trail |
| Pine Hill Gap Trail |
| Piney Branch Trail |

| |
|---|
| Piney Ridge Trail |
| Pocosin Hollow Trail |
| Pole Bridge Link Trail |
| Powell Mountain Trail |
| Presidents Cabin Trail |
| Reflector Oven Bottom Trail |
| Reflector Oven Top Trail |
| Reflector-Gods Access Trail |
| Ridge Trail |
| Riprap Trail |
| Robertson Mountain Trail |
| Rocky Branch Trail |
| Rocky Mountain Run Trail |
| Rockytop Trail |
| Rose River Loop Trail |
| Saddle Trail |
| Sams Ridge Trail |
| Skyland-Big Meadows Trail |
| Slaughter Trail |
| Snead Farm Loop Trail |
| South River Falls Trail |
| Springhouse Trail |
| Staunton River Trail |
| Stony Man Ovlk Privy Trail |
| Stony Mountain Trail |
| Stull Run Trail |
| Sugarloaf Trail |
| Sunset Walls Trail |
| Thompson Hollow Trail |
| Thornton River Trail (Upper and Lower) |
| Traces Trail |
| Trayfoot Mountain Trail |
| Turk Branch Trail |
| Tuscarora Trail |
| Upper Dark Hollow Trail |
| Weddlewood Trail |
| West Naked Creek Trail |
| White Rocks Trail |
| Whiteoak Canyon Trail |
| Wildcat Ridge Trail |

| **Recommended Vistas for Sampling in Shenandoah** |
|---|
| Loft Mountain Overlook |
| Blackrock Summit |
| Hawksbill Summit |
| Old Rag Summit |
| Pinnacles Overlook |
| Spitler Knoll Overlook |
| Tanners Ridge Overlook |
| The Oaks Overlook |
| Thorofare Mountain Overlook |

**FIGURE 14: TICK HABITAT SUITABILITY IN GREAT SMOKY MOUNTAINS NATIONAL PARK**

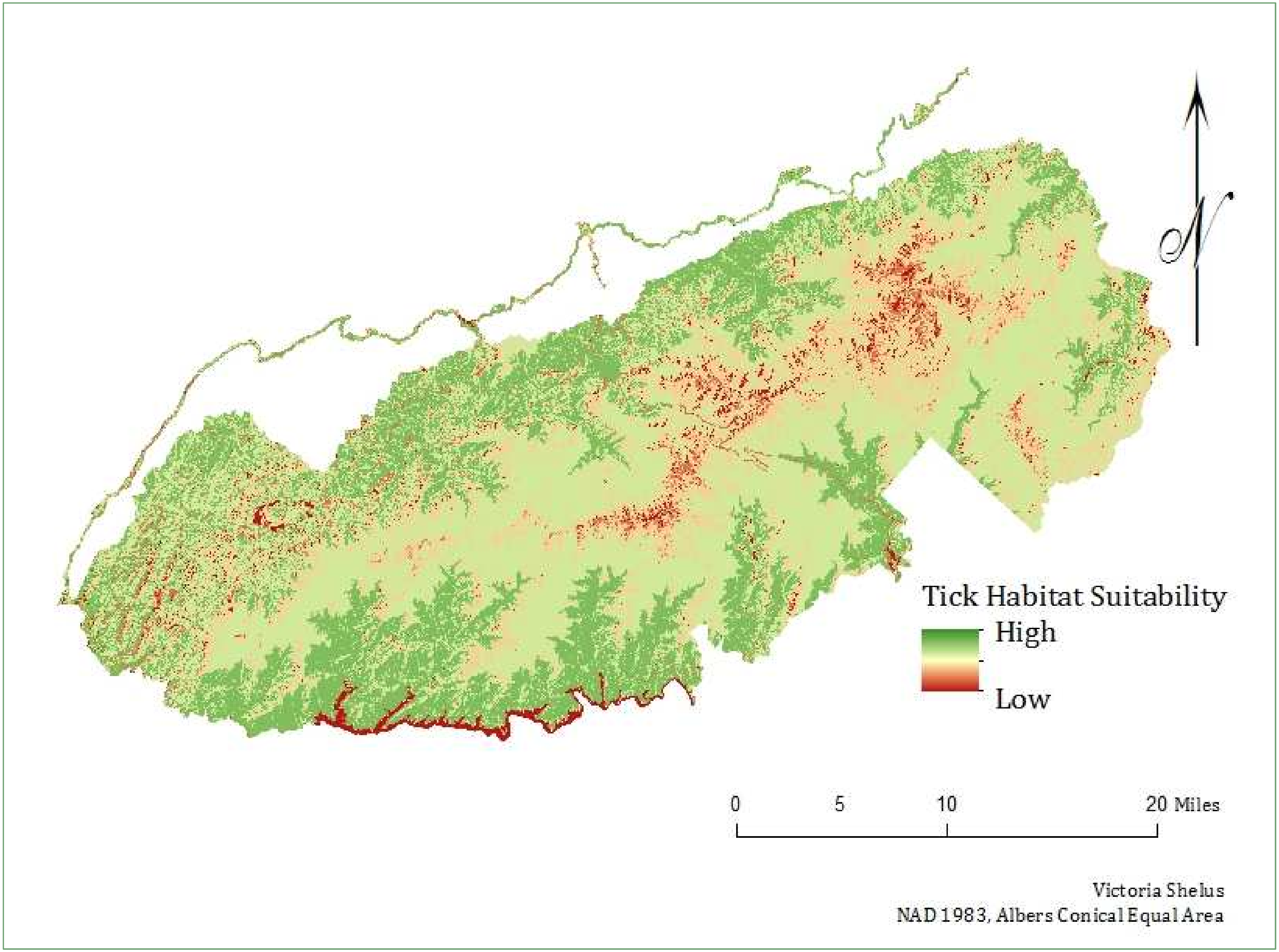


**FIGURE 15: RECOMMENDED SAMPLING AREAS IN GREAT SMOKY MOUNTAINS NATIONAL PARK**

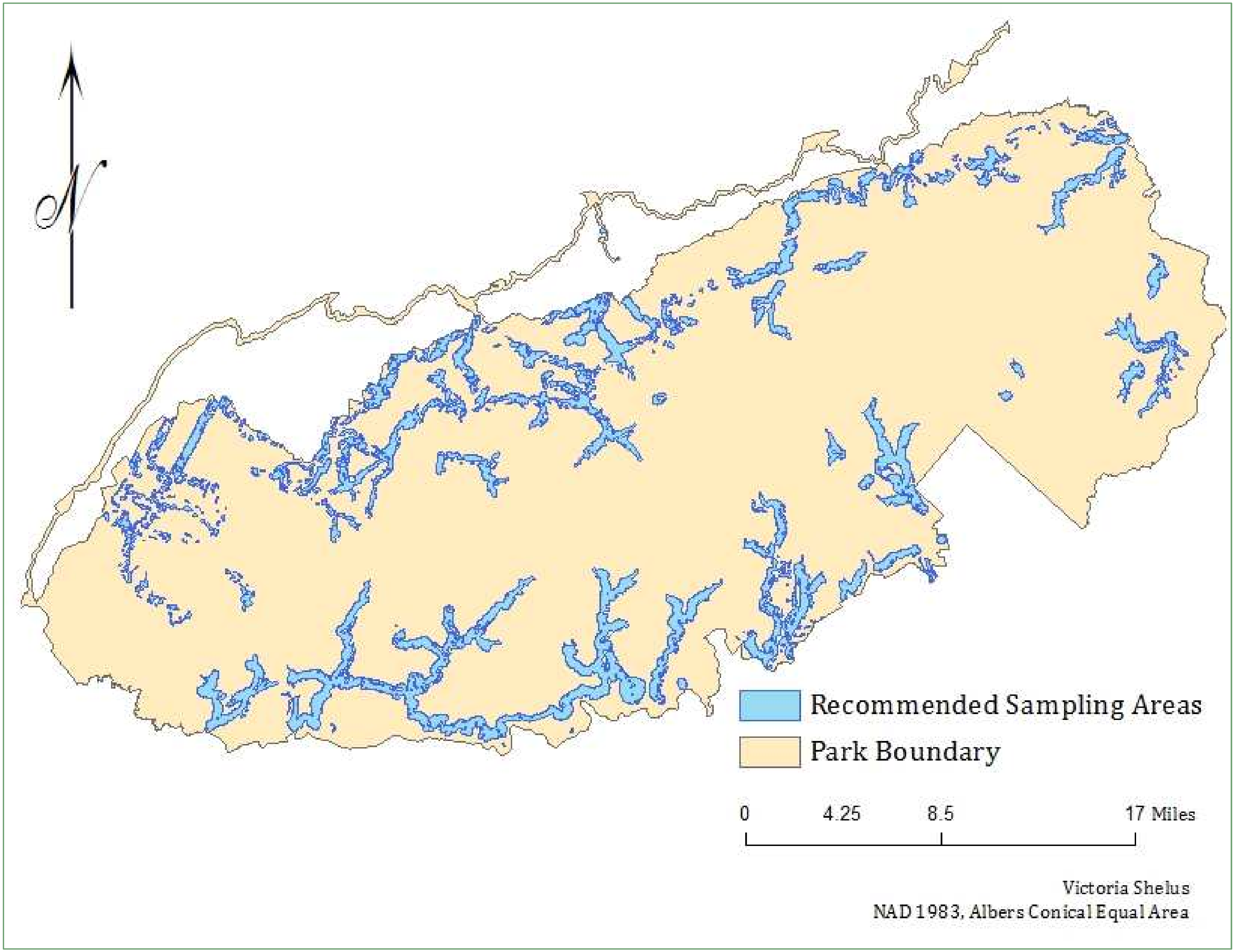


**Table 10: Recommended Sampling Trails, Vistas, and Campgrounds in Great Smoky Mountains National Park**

| Trails |
|---|
| Abrams Falls Trail |
| Ace Gap Trail |
| Albright Grove Loop Trail |
| Anthony Creek Trail |
| Appalachian Trail |
| Balsam Point Quiet Walkway |
| Baskins Creek Trail |
| Baxter Creek Trail |
| Bear Creek Trail |
| Beard Cane Trail |
| Beech Gap Trail |
| Big Creek Trail |
| Big Fork Ridge Trail |
| Big White Oak Quiet Walkway |
| Bone Valley Trail |
| Boogerman Trail |
| Bote Mountain Trail |
| Bradley Fork Trail |
| Brushy Mountain Trail |
| Bullhead Trail |
| Cabin Flats Trail |
| Cades Cove Nature Trail |
| Caldwell Fork Trail |
| Camel Gap Trail |
| Cane Creek Trail |
| Cataloochee Horse Trail |
| Cataract Falls spur |
| Chasteen Creek Trail |
| Chestnut Branch Trail |
| Chestnut Top Trail |
| Cold Spring Gap Trail |
| Collins Creek Quiet Walkway |
| Cooper Creek Trail |
| Cosby Trail |
| Cove Hardwood Nature Trail |
| Cove Mountain Trail |
| Crib Gap Trail |
| Crooked Arm Ridge Trail |
| Cucumber Gap Trail |
| Curry Mountain Trail |
| Deep Creek Trail |
| Deep Low Gap Trail |
| Dry Sluice Gap Trail |
| Eagle Creek Trail |
| Elkmont Nature Trail |
| Fighting Creek Nature Trail |
| Finley Cane Trail |
| Fork Ridge Trail |
| Forney Creek Trail |
| Gabes Mountain Trail |
| Gatlinburg Trail |
| Gold Mine Trail |
| Goldmine Loop Trail |
| Goshen Prong Trail |
| Grapeyard Ridge Trail |
| Greenbrier Ridge Trail |
| Gregory Trail (Bald and Ridge) |
| Gunter Fork Trail |
| Hannah Mountain Trail |
| Hatcher Mountain Trail |
| Hazel Creek Trail |
| Hickory Flats Quiet Walkway |
| Huskey Gap Trail |
| Hyatt Ridge Trail |
| Indian Creek Trail |
| Indian Grave Gap Trail |
| Jakes Creek Trail |
| Jenkins Ridge Trail |
| Jonas Creek Trail |
| Juney Whank Falls Trail |
| Kanati Fork Trail |
| Kephart Prong Trail |
| Lakeshore Trail |
| Lakeview Quiet Walkway |
| Laurel Falls Trail |
| Lead Cove Trail |
| Little Bottoms Trail |
| Little Brier Gap Trail |
| Little Cataloochee Trail |
| Little Greenbrier Trail |
| Little River Trail |
| Long Bunk Trail |
| Long Hungry Ridge Trail |
| Loop Trail |
| Lost Cove Trail |
| Low Gap Trail |
| Lower Mount Cammerer Trail |
| Lumber Ridge Trail |
| Lynn Camp Prong Trail |
| Maddron Bald Trail |
| Martins Gap Trail |

| |
|---|
| McKee Branch Trail |
| Meigs Creek Trail |
| Meigs Mountain Trail |
| Metcalf Bottoms Trail |
| Middle Prong Trail |
| Mingus Creek Trail |
| Newton Bald Trail |
| Noah 'Bud' Ogle Place Nature Trail |
| Noland Creek Trail |
| Oconaluftee River Trail |
| Old Settlers Trail |
| Old Sugarlands Trail |
| Ollie Cove Trail |
| Palmer Creek Trail |
| Panther Creek Trail |
| Pole Road Creek Trail |
| Porters Creek Trail |
| Pretty Hollow Gap Trail |
| Rabbit Creek Trail |
| Rainbow Falls Trail |
| Ramsey Cascades Trail |
| Rich Mountain Trail |
| Riverview Quiet Walkway |
| Rough Creek Trail |
| Rough Fork Trail |
| Roundtop Trail |
| Russell Field Trail |
| Schoolhouse Gap Trail |
| Scott Mountain Trail |

| |
|---|
| Smokemont Loop Trail (Loop, Nature, and Stables) |
| Snake Den Ridge Trail |
| Springhouse Branch Trail |
| Stone Pile Gap Trail |
| Sugarland Mountain Trail |
| Sugarlands Valley Nature Trail |
| Sunkota Ridge Trail |
| Swallow Fork Trail |
| Thomas Divide Trail |
| Thunderhead Prong Quiet Walkway |
| Tow String Horse Trail |
| Trillium Gap Trail |
| Turkeypen Ridge Trail |
| Twentymile Trail |
| Twin Creeks Trail |
| West Prong Trail |
| Wet Bottom Trail |
| White Oak Branch Trail |
| Wolf Ridge Trail |
| |
| **Points of Interest** |
| Ravenfork Overlook |
| |
| **Backcountry Campsites (#)** |
| 3, 10-12, 14, 16, 18, 20, 24, 32-34, 36-37, 39-41, 46, 49-51, 53-55, 58, 62-65, 67, 69-72, 74-77, 82-83, 85, 88-93, 95-98 |

## Discussion

The primary goal of this project was to assess tick-borne disease risk in the six National Park Service units located along the Appalachian Trail (AT). These NPS units are the Delaware Water Gap National Recreation Area, Harpers Ferry National Historical Park, Chesapeake and Ohio National Historical Park, Shenandoah National Park, the Blue Ridge Parkway, and Great Smoky Mountains National Park. The focus was on three ticks, *Ixodes scapularis*, the Black-legged tick or Deer tick, *Amblyomma americanum*, the Lone star tick, and *Dermacentor variabilis,* the American dog tick or Wood tick. These ticks transmit the agents that cause Lyme disease, Rocky Mountain Spotted Fever, Anaplasmosis, Tularemia, Ehrlichiosis, Southern Tick Associated Rash Illness, and Babesiosis.

Acarological data is required to study tick-borne disease risk on public lands such as national parks because of numerous challenges associated with the use of epidemiological data. A literature review summarizing current knowledge on the abundance, infection prevalence, and seasonal phenology of ticks along the Appalachian Trail found that current acarological data is insufficient and outdated.

The most recent data on tick distribution and infection prevalence for the national parks located along the AT are between 10 and 20 years old. *I. scapularis* and *D. variabilis* are known to be abundant in the Delaware Water Gap National Recreation Area [37] and Great Smoky Mountains National Park [43] respectively, but knowledge gaps exist for the other ticks and NPS units. The greatest risk for tick bites occurs between April and July, however insufficient data was available to differentiate between regions and NPS units along the trail.

Research has shown that the distribution of tick vectors is related to environmental factors. *Ixodes scapularis* abundance and infection prevalence is associated with climate, specifically precipitation, temperature, and humidity; landscape characteristics such as vegetation, soil type, and forest fragmentation; and host diversity and abundance. Several of these ecological drivers of risk were quantified for the national park service units and the surrounding residential areas to determine their similarity and the possibility for the transferability of risk estimates.

Measures of land cover, landscape structure, and elevation were quantified for the national parks and the surrounding counties, and differences with the percentage of forested area and the amount of edge habitat were found to be statistically significant. Overall, there was more forested area within the NPS units, compared with larger areas classified as developed, agriculture, and wetlands in the surrounding counties. The greatest difference between a NPS unit and the surrounding area with regards to forest cover was Delaware Water Gap National Recreation Area. Fragmentation, measured by the number of meters per hectare of natural-converted edge, was higher in the areas outside of the parks, with the greatest contrast between Great Smoky Mountains National Park and the surrounding counties. The difference in elevation varied between NPS units

Given the lack of data in the National Park Service units on the tick species present, their infection prevalence, and their seasonal phenology, as well as the differences in ecological drivers of risk between parks and the surrounding areas, the true risk of tick-borne diseases in national parks is unknown, and likely under recognized. Visitors might also be at risk because they are engaged in outdoor activities where exposure to ticks is likely.

It is recommended that tick sampling as part of a larger tick-borne disease surveillance program be implemented in the national parks. As a starting point to further study, this project modeled general tick habitat suitability for the national park units along the Appalachian Trail based on land cover, elevation and moisture. Potential tick sampling sites were selected based on areas of high tick habitat suitability and high visitor use. This was completed for Delaware Water Gap National Recreation Area, Harpers Ferry National Historical Park, Shenandoah National Park, and the Great Smoky Mountains National Park. Given the large number of trails in the recommended sampling areas for Shenandoah and the Great Smoky Mountains, park management should use their judgment and expertise to narrow the list so that sampling is feasible.

It is important to emphasize that this model of tick habitat suitability is overly simplified. It generalizes the habitat requirements of the three tick species, assuming similar preferred conditions in the absence of data. Additionally, numerous assumptions are made about the appropriate cutoffs for suitable and unsuitable habitat characteristics.

Ideally, this information would be based on field sampling. The inclusion of additional information, such as soil type, fragmentation, and host density could improve the model.

This model should not be used as the basis for any interventions that require specific knowledge of tick locations, such as the application of chemical or biological agents, treatment of hosts with acaricides, or landscape management, which are incompatible with the NPS mission except in severe disease outbreaks. However, it can serve as a starting point for behavior modification and education campaigns focused on providing visitors information about the risks of tick-borne diseases and personal protection measures that can be taken. Areas identified as high risk can be targeted first. Additionally, the recommendations of sampling sites can be used if more in-depth study of tick borne diseases in these national park service units is undertaken.

This report has demonstrated a need for increased tick sampling and testing for pathogens within the NPS units. It is important that visitors and employees understand the risk of tick-borne diseases while visiting these natural and historic landmarks, and have the information they need to make decisions to protect their health.

## Acknowledgements

I would like to thank my supervisors and project collaborators, Rebecca Eisen, at the Centers for Disease Control and Prevention, and Amy Chanlongbutra with the National Park Service for their guidance throughout the project. My advisor at the Nicholas School of the Environment, Dean Urban, provided many helpful suggestions and support. Finally, a huge thank you to my friends and family for everything they do.

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# Appendix

I. Disease Case and Incidence Data [81]

**TABLE 11: APPALACHIAN TRAIL COUNTIES AND LYME DISEASE CASES AND INCIDENCE (PER 100,000 PEOPLE)**

| | | 1992 - 1996 | | 1997 - 2001 | | 2001 - 2006 | |
|---|---|---|---|---|---|---|---|
| **County** | State | Cases | Incidence | Cases | Incidence | Cases | Incidence |
| Somerset | Maine | 2 | 3.93 | 5 | 9.83 | 13 | 25.55 |
| Piscataquis | Maine | 1 | 5.80 | 2 | 11.60 | 2 | 11.60 |
| Franklin | Maine | 2 | 6.79 | 4 | 13.57 | 12 | 40.72 |
| Oxford | Maine | 3 | 5.48 | 9 | 16.44 | 11 | 20.09 |
| Coos | New Hampshire | 13 | 39.26 | 11 | 33.22 | 12 | 36.24 |
| Grafton | New Hampshire | 11 | 13.46 | 19 | 23.24 | 30 | 36.70 |
| Carroll | New Hampshire | 16 | 36.64 | 9 | 20.61 | 29 | 66.41 |
| Windsor | Vermont | 15 | 26.12 | 15 | 26.12 | 21 | 36.57 |
| Rutland | Vermont | 3 | 4.73 | 9 | 14.20 | 22 | 34.70 |
| Bennington | Vermont | 6 | 16.22 | 17 | 45.95 | 99 | 267.61 |
| Windham | Vermont | 7 | 15.83 | 15 | 33.92 | 40 | 90.46 |
| Berkshire | Massachusetts | 4 | 2.96 | 144 | 106.70 | 350 | 259.35 |
| Litchfield | Connecticut | 483 | 265.10 | 1777 | 975.34 | 1892 | 1038.46 |
| Fairfield | Connecticut | 2384 | 270.12 | 4842 | 548.63 | 2759 | 312.61 |
| Dutchess | New York | 4496 | 1604.85 | 6172 | 2203.11 | 6407 | 2286.99 |
| Orange | New York | 1071 | 313.74 | 2276 | 666.73 | 2649 | 776.00 |
| Putnam | New York | 1240 | 1295.11 | 1055 | 1101.89 | 1095 | 1143.66 |
| Rockland | New York | 401 | 139.84 | 403 | 140.54 | 980 | 341.76 |
| Westchester | New York | 4724 | 511.55 | 2102 | 227.62 | 2552 | 276.35 |
| Sussex | New Jersey | 88 | 61.04 | 375 | 260.12 | 1333 | 924.63 |
| Passaic | New Jersey | 31 | 6.34 | 76 | 15.54 | 290 | 59.30 |
| Warren | New Jersey | 193 | 188.41 | 609 | 594.51 | 946 | 923.49 |
| Monroe | Pennsylvania | 11 | 7.93 | 83 | 59.85 | 328 | 236.50 |
| Carbon | Pennsylvania | 11 | 18.71 | 16 | 27.21 | 36 | 61.22 |
| Northampton | Pennsylvania | 220 | 82.38 | 315 | 117.95 | 927 | 347.11 |
| Schuylkill | Pennsylvania | 18 | 11.97 | 27 | 17.96 | 76 | 50.55 |
| Lehigh | Pennsylvania | 78 | 24.99 | 243 | 77.86 | 817 | 261.78 |
| Berks | Pennsylvania | 111 | 29.71 | 554 | 148.27 | 1803 | 482.55 |
| Dauphin | Pennsylvania | 32 | 12.71 | 53 | 21.05 | 296 | 117.55 |
| Perry | Pennsylvania | 4 | 9.17 | 11 | 25.23 | 66 | 151.37 |
| Lebanon | Pennsylvania | 5 | 4.16 | 57 | 47.37 | 280 | 232.70 |
| Cumberland | Pennsylvania | 15 | 7.02 | 65 | 30.42 | 240 | 112.32 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Franklin | Pennsylvania | 17 | 13.15 | 28 | 21.65 | 121 | 93.57 |
| Washington | Maryland | 9 | 6.82 | 29 | 21.98 | 180 | 136.44 |
| Frederick | Maryland | 8 | 4.10 | 90 | 46.09 | 467 | 239.15 |
| Jefferson | West Virginia | 1 | 2.37 | 10 | 23.70 | 39 | 92.44 |
| Monroe | West Virginia | 2 | 13.71 | 1 | 6.86 | 1 | 6.86 |
| Loudoun | Virginia | 8 | 4.72 | 153 | 90.21 | 417 | 245.87 |
| Clarke | Virginia | 0 | 0.00 | 2 | 15.81 | 8 | 63.23 |
| Warren | Virginia | 3 | 9.50 | 13 | 41.16 | 13 | 41.16 |
| Fauquier | Virginia | 2 | 3.63 | 6 | 10.88 | 47 | 85.24 |
| Rappahannock | Virginia | 1 | 14.32 | 0 | 0.00 | 6 | 85.92 |
| Rockingham | Virginia | 2 | 2.95 | 6 | 8.86 | 5 | 7.38 |
| Page | Virginia | 3 | 12.94 | 1 | 4.31 | 4 | 17.26 |
| Madison | Virginia | 0 | 0.00 | 3 | 23.96 | 1 | 7.99 |
| Augusta | Virginia | 3 | 4.57 | 5 | 7.62 | 2 | 3.05 |
| Greene | Virginia | 0 | 0.00 | 2 | 13.12 | 4 | 26.24 |
| Albemarle | Virginia | 2 | 2.52 | 11 | 13.88 | 23 | 29.03 |
| Rockbridge | Virginia | 1 | 4.81 | 3 | 14.42 | 3 | 14.42 |
| Nelson | Virginia | 6 | 41.54 | 1 | 6.92 | 0 | 0.00 |
| Amherst | Virginia | 3 | 9.41 | 0 | 0.00 | 1 | 3.14 |
| Botetourt | Virginia | 1 | 3.28 | 0 | 0.00 | 0 | 0.00 |
| Craig | Virginia | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Bedford | Virginia | 10 | 16.56 | 9 | 14.91 | 3 | 4.97 |
| Giles | Virginia | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Roanoke | Virginia | 0 | 0.00 | 2 | 2.33 | 2 | 2.33 |
| Tazewell | Virginia | 2 | 4.48 | 0 | 0.00 | 3 | 6.73 |
| Bland | Virginia | 0 | 0.00 | 0 | 0.00 | 1 | 14.55 |
| Montgomery | Virginia | 5 | 5.98 | 8 | 9.57 | 5 | 5.98 |
| Wythe | Virginia | 0 | 0.00 | 1 | 3.62 | 1 | 3.62 |
| Smyth | Virginia | 0 | 0.00 | 0 | 0.00 | 1 | 3.02 |
| Washington | Virginia | 2 | 3.91 | 0 | 0.00 | 0 | 0.00 |
| Grayson | Virginia | 0 | 0.00 | 1 | 5.58 | 0 | 0.00 |
| Sullivan | Tennessee | 2 | 1.31 | 1 | 0.65 | 1 | 0.65 |
| Johnson | Tennessee | 0 | 0.00 | 0 | 0.00 | 1 | 5.71 |
| Carter | Tennessee | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Greene | Tennessee | 3 | 4.77 | 2 | 3.18 | 0 | 0.00 |
| Unicoi | Tennessee | 1 | 5.66 | 0 | 0.00 | 1 | 5.66 |
| Cocke | Tennessee | 1 | 2.98 | 0 | 0.00 | 1 | 2.98 |
| Sevier | Tennessee | 0 | 0.00 | 1 | 1.41 | 0 | 0.00 |
| Blount | Tennessee | 2 | 1.89 | 1 | 0.94 | 0 | 0.00 |
| Avery | North Carolina | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Mitchell | North Carolina | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Yancey | North Carolina | 0 | 0.00 | 0 | 0.00 | 1 | 5.63 |
| Madison | North Carolina | 2 | 10.19 | 3 | 15.28 | 2 | 10.19 |
| Haywood | North Carolina | 1 | 1.85 | 0 | 0.00 | 1 | 1.85 |
| Swain | North Carolina | 12 | 92.54 | 10 | 77.11 | 1 | 7.71 |
| Graham | North Carolina | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Macon | North Carolina | 1 | 3.35 | 1 | 3.35 | 0 | 0.00 |
| Clay | North Carolina | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Rabun | Georgia | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Towns | Georgia | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Fannin | Georgia | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Union | Georgia | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Gilmer | Georgia | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Habersham | Georgia | 1 | 2.79 | 0 | 0.00 | 0 | 0.00 |
| White | Georgia | 0 | 0.00 | 0 | 0.00 | 0 | 0.00 |
| Lumpkin | Georgia | 0 | 0.00 | 0 | 0.00 | 1 | 4.76 |

II. Geospatial Methods

**TABLE 12: LANDSAT 5 TM IMAGES USED FOR MOISTURE CALCULATIONS**

| NPS Unit | Path/Row | Image Date |
|---|---|---|
| Delaware Water Gap National Recreation Area | 14/31<br>14/32 | 7/30/2011<br>7/30/2011 |
| Harpers Ferry National Historical Park | 16/33 | 6/10/2011 |
| Shenandoah National Park | 16/33<br>16/34 | 7/12/2011<br>7/28/2011 |
| Great Smoky Mountains National Park | 19/35 | 8/31/2010 |

**TABLE 13: RECLASSIFICATION SCHEME FOR TICK HABITAT AND SAMPLING SITE SUITABILITY**

| | | Land Cover (40%) | Elevation (30%) | Moisture (30%) |
|---|---|---|---|---|
| Highly Unsuitable | 1 | Open Water, Developed Medium and High Intensity, Barren Land | 1600 + meters | 200 – 266 |
| | 2 | Cultivated Crops | | |
| | 3 | Woody and Emergent Herbaceous Wetlands | 1000 – 1600 meters | -15 – 80 |
| | 4 | Developed Open Space and Low Intensity | | |
| | 5 | | 600 – 1000 meters | |
| | 6 | Pasture Hay, Grassland Herbaceous | | |
| | 7 | Shrub/Scrub | 300 – 600 meters | |
| | 8 | Evergreen Forest | | 80 – 120, 180 - 200 |
| | 9 | Mixed Forest | 0 – 300 meters | |
| Highly Suitable | 10 | Deciduous Forest | | 120 - 180 |

III. Land Cover Comparison

**TABLE 14: LAND COVER CLASSIFICATION (BY AREA AND %) IN EACH NPS UNIT AND THE SURROUNDING COUNTIES**

| | Delaware Water Gap | | | | Harpers Ferry | | | | Chesapeake and Ohio Canal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NPS Unit | | Counties | | NPS Unit | | Counties | | NPS Unit | | Counties | |
| **Class** | Area (ha) | % | Area (ha) | % | Area (ha) | % | Area (ha) | % | Area (ha) | % | Area (ha) | % |
| Open Water | 1249 | 4 | 13377 | 2 | 56 | 4 | 6287 | 1 | 458 | 5 | 17426 | 1 |
| Developed, Open Space | 1509 | 5 | 60046 | 10 | 159 | 11 | 40976 | 8 | 453 | 5 | 123182 | 10 |
| Developed, Low Intensity | 93 | 0 | 17711 | 3 | 32 | 2 | 24987 | 5 | 116 | 1 | 76488 | 6 |
| Developed, Medium Intensity | 15 | 0 | 6962 | 1 | 10 | 1 | 8256 | 2 | 25 | 0 | 31635 | 3 |
| Developed, High Intensity | 2 | 0 | 2150 | 0 | 0 | 0 | 2167 | 0 | 6 | 0 | 9241 | 1 |
| Barren Land (Rock/Sand/Clay) | 0 | 0 | 1109 | 0 | 0 | 0 | 537 | 0 | 4 | 0 | 2079 | 0 |
| Deciduous Forest | 14023 | 50 | 301755 | 50 | 936 | 62 | 141148 | 29 | 5428 | 64 | 565076 | 45 |
| Evergreen Forest | 1221 | 4 | 13686 | 2 | 33 | 2 | 12456 | 3 | 176 | 2 | 27359 | 2 |
| Mixed Forest | 6583 | 24 | 39192 | 6 | 30 | 2 | 5111 | 1 | 203 | 2 | 20812 | 2 |
| Shrub/Scrub | 67 | 0 | 6749 | 1 | 0 | 0 | 2730 | 1 | 62 | 1 | 5943 | 0 |
| Grassland/Herbaceous | 25 | 0 | 1152 | 0 | 0 | 0 | 1087 | 0 | 4 | 0 | 2503 | 0 |
| Pasture/Hay | 542 | 2 | 36955 | 6 | 223 | 15 | 156227 | 32 | 649 | 8 | 251665 | 20 |
| Cultivated Crops | 1247 | 4 | 67420 | 11 | 7 | 0 | 74965 | 16 | 221 | 3 | 95400 | 8 |
| Woody Wetlands | 1370 | 5 | 38724 | 6 | 17 | 1 | 4621 | 1 | 720 | 8 | 12286 | 1 |
| Emergent Herbaceous Wetlands | 21 | 0 | 2185 | 0 | 0 | 0 | 630 | 0 | 10 | 0 | 1350 | 0 |

| | Shenandoah | | | | Blue Ridge Parkway | | | | Great Smoky Mountains | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NPS Unit | | Counties | | NPS Unit | | Counties | | NPS Unit | | Counties | |
| **Class** | Area (ha) | % | Area (ha) | % | Area (ha) | % | Area (ha) | % | Area (ha) | % | Area (ha) | % |
| Open Water | 0 | 0 | 5406 | 1 | 64 | 0 | 27477 | 1 | 1670 | 1 | 11678 | 2 |
| Developed, Open Space | 2002 | 3 | 55094 | 6 | 7616 | 21 | 223695 | 6 | 1875 | 1 | 45487 | 6 |
| Developed, Low Intensity | 43 | 0 | 18512 | 2 | 181 | 0 | 53588 | 1 | 18 | 0 | 10312 | 1 |
| Developed, Medium Intensity | 5 | 0 | 3129 | 0 | 15 | 0 | 12564 | 0 | 3 | 0 | 3000 | 0 |
| Developed, High Intensity | 1 | 0 | 1021 | 0 | 0 | 0 | 3873 | 0 | 0 | 0 | 866 | 0 |
| Barren Land (Rock/Sand/Clay) | 18 | 0 | 640 | 0 | 6 | 0 | 2972 | 0 | 76 | 0 | 989 | 0 |
| Deciduous Forest | 72306 | 92 | 430221 | 47 | 24349 | 66 | 2237086 | 62 | 167475 | 80 | 430121 | 58 |
| Evergreen Forest | 2333 | 3 | 64991 | 7 | 1887 | 5 | 226307 | 6 | 29355 | 14 | 52691 | 7 |
| Mixed Forest | 1493 | 2 | 46295 | 5 | 829 | 2 | 117757 | 3 | 7616 | 4 | 33071 | 4 |
| Shrub/Scrub | 0 | 0 | 665 | 0 | 193 | 1 | 35720 | 1 | 694 | 0 | 12060 | 2 |
| Grassland/Herbaceous | 0 | 0 | 1527 | 0 | 38 | 0 | 39455 | 1 | 54 | 0 | 9711 | 1 |
| Pasture/Hay | 12 | 0 | 266418 | 29 | 1435 | 4 | 623753 | 17 | 840 | 0 | 116974 | 16 |
| Cultivated Crops | 0 | 0 | 18477 | 2 | 14 | 0 | 16780 | 0 | 46 | 0 | 8663 | 1 |
| Woody Wetlands | 0 | 0 | 456 | 0 | 19 | 0 | 3022 | 0 | 107 | 0 | 1651 | 0 |
| Emergent Herbaceous Wetlands | 0 | 0 | 112 | 0 | 0 | 0 | 113 | 0 | 0 | 0 | 31 | 0 |

**FIGURE 16: MAP OF LAND COVER IN THE DELAWARE WATER GAP NATIONAL RECREATION AREA AND THE SURROUNDING COUNTIES**

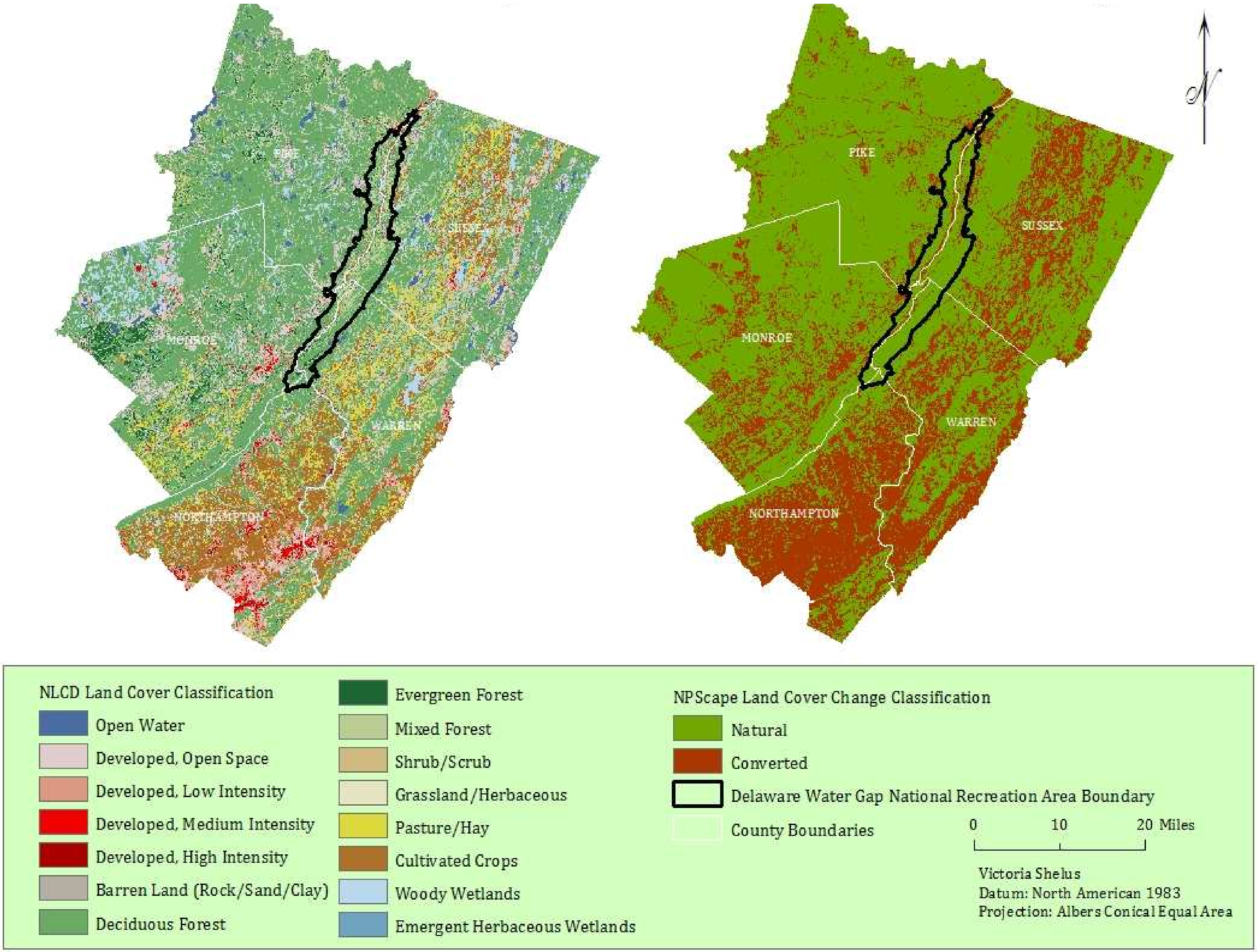

**FIGURE 17: MAP OF LAND COVER IN HARPERS FERRY NATIONAL HISTORICAL PARK AND THE SURROUNDING COUNTIES**

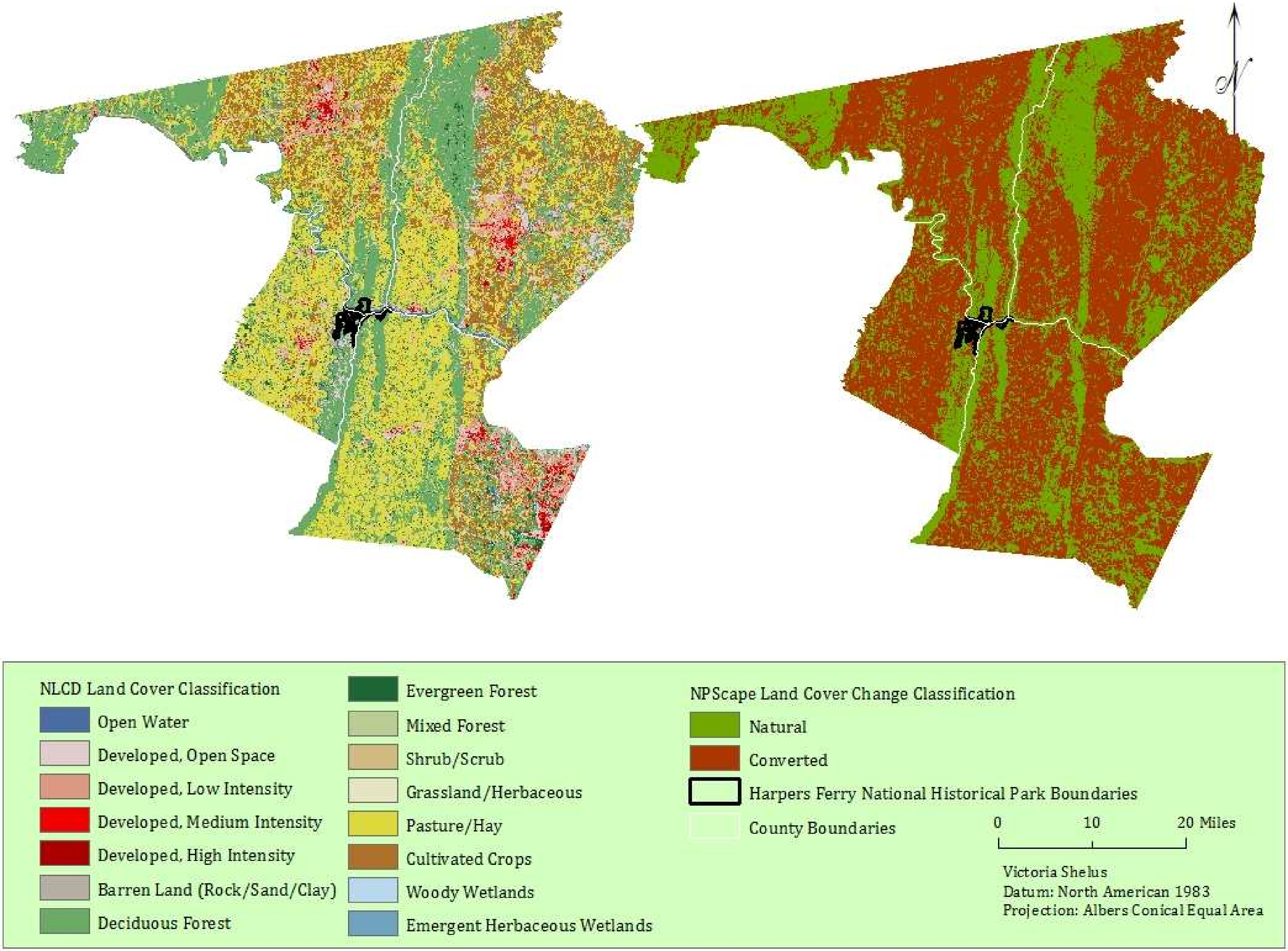

**FIGURE 18: MAP OF LAND COVER IN CHESAPEAKE AND OHIO CANAL NATIONAL HISTORICAL PARK AND THE SURROUNDING COUNTIES**

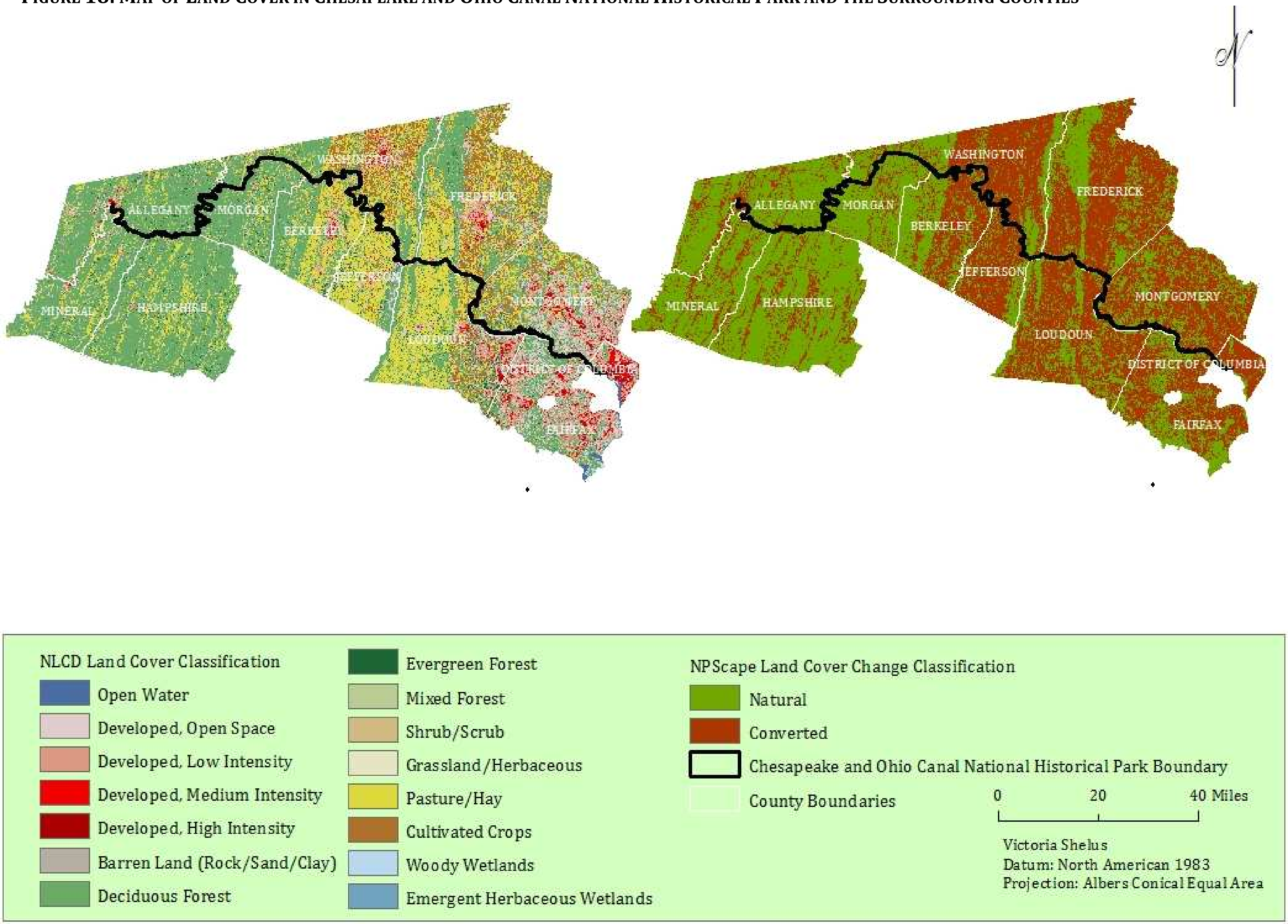

**FIGURE 19: MAP OF LAND COVER IN SHENANDOAH NATIONAL PARK AND THE SURROUNDING COUNTIES**

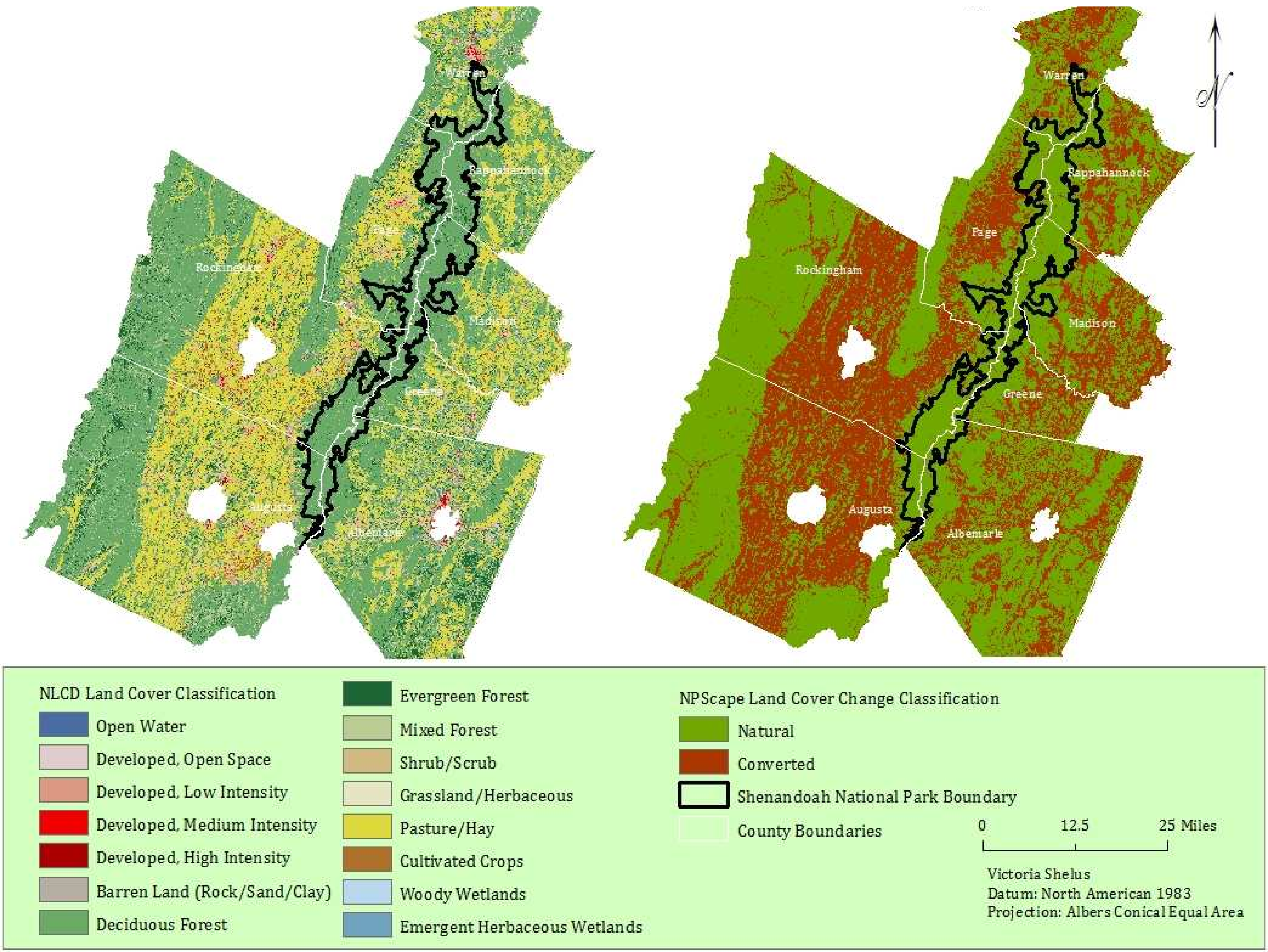

**FIGURE 20: MAP OF LAND COVER IN BLUE RIDGE PARKWAY AND THE SURROUNDING COUNTIES**

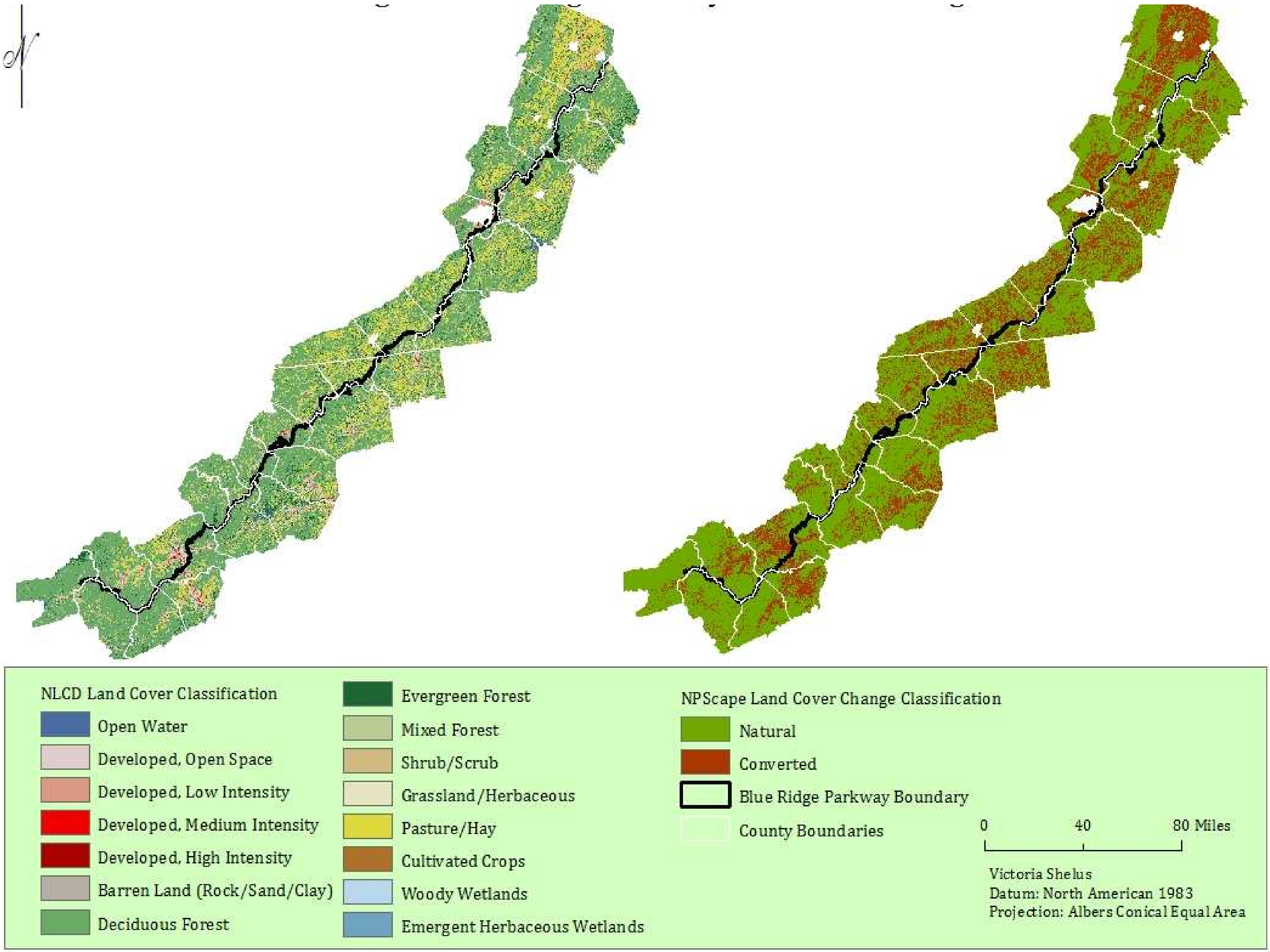

**FIGURE 21: MAP OF LAND COVER IN GREAT SMOKY MOUNTAINS NATIONAL PARK AND THE SURROUNDING COUNTIES**

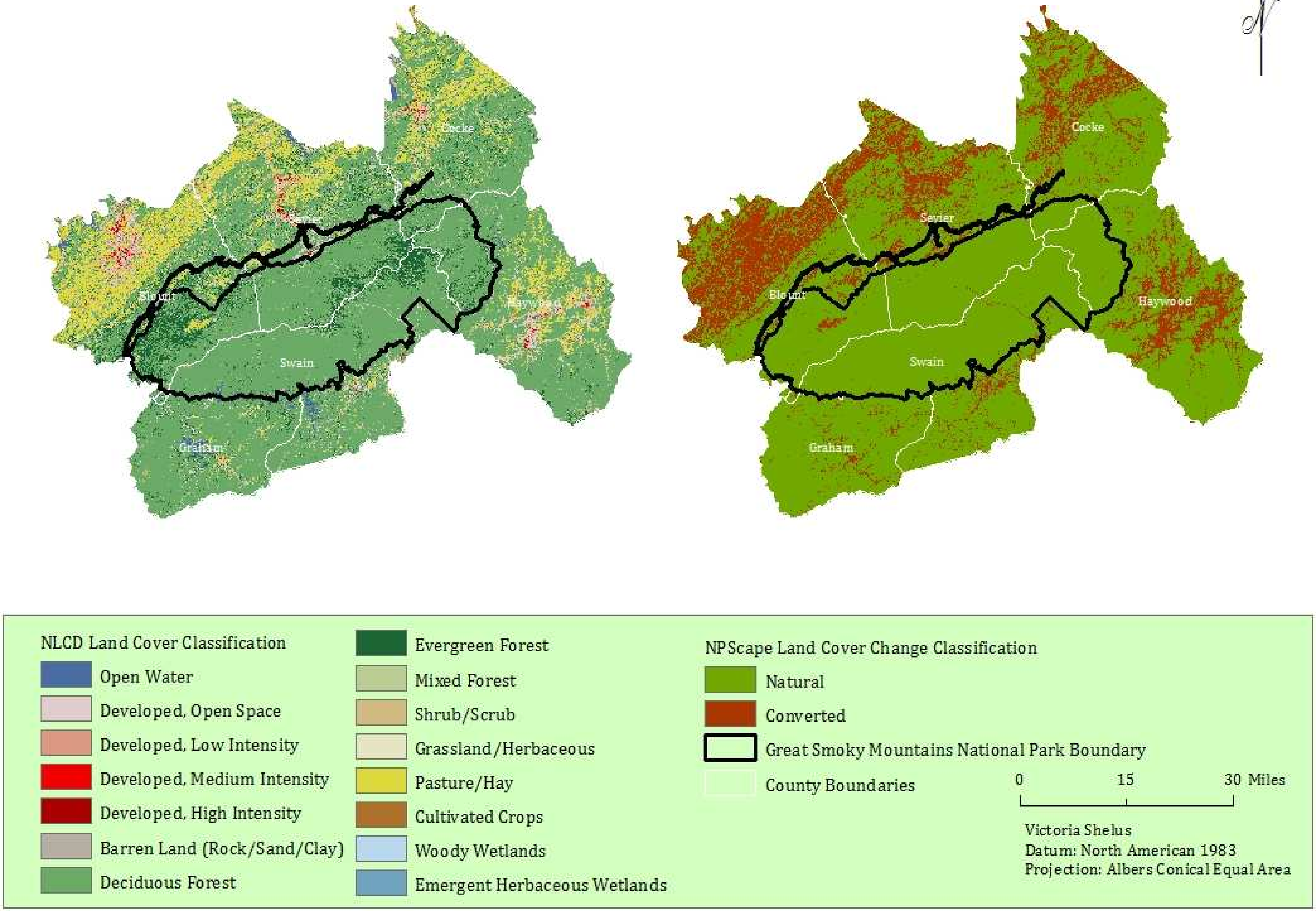

**FIGURE 22: COMPARISON OF LAND COVER TYPES: DELAWARE WATER GAP NATIONAL RECREATION AREA**

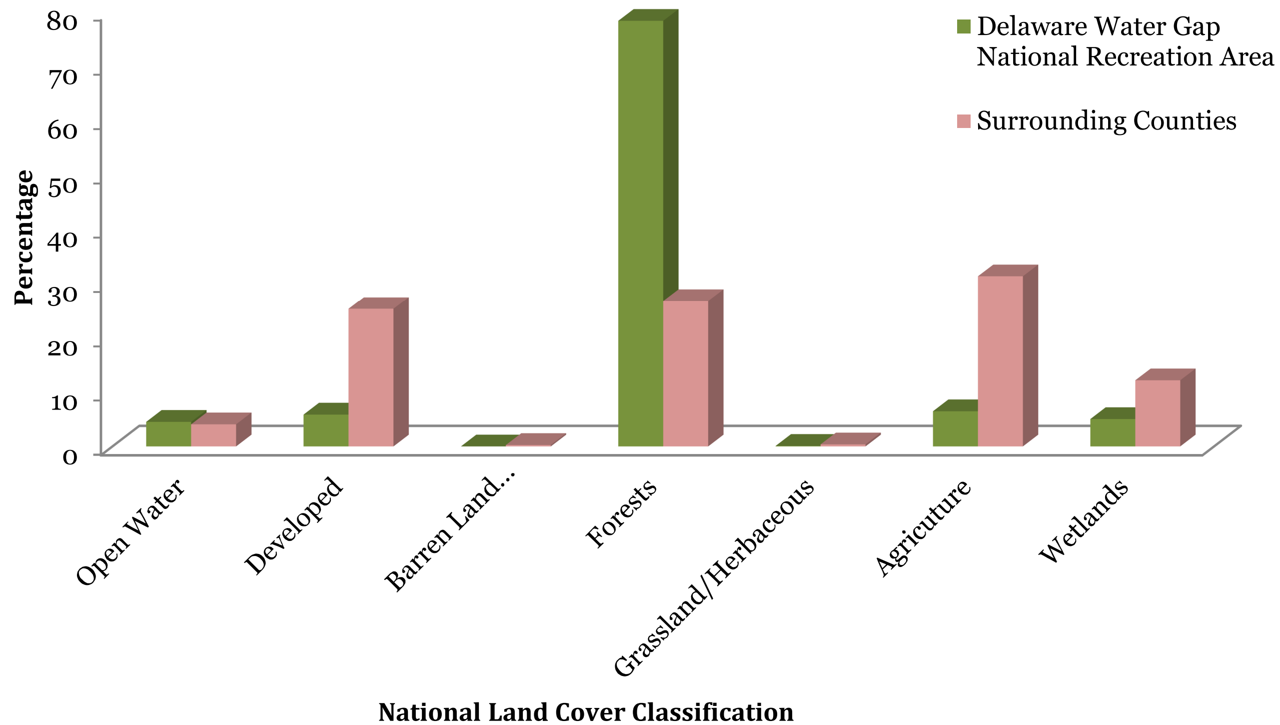


**FIGURE 23: COMPARISON OF LAND COVER TYPES: HARPERS FERRY NATIONAL HISTORICAL PARK**

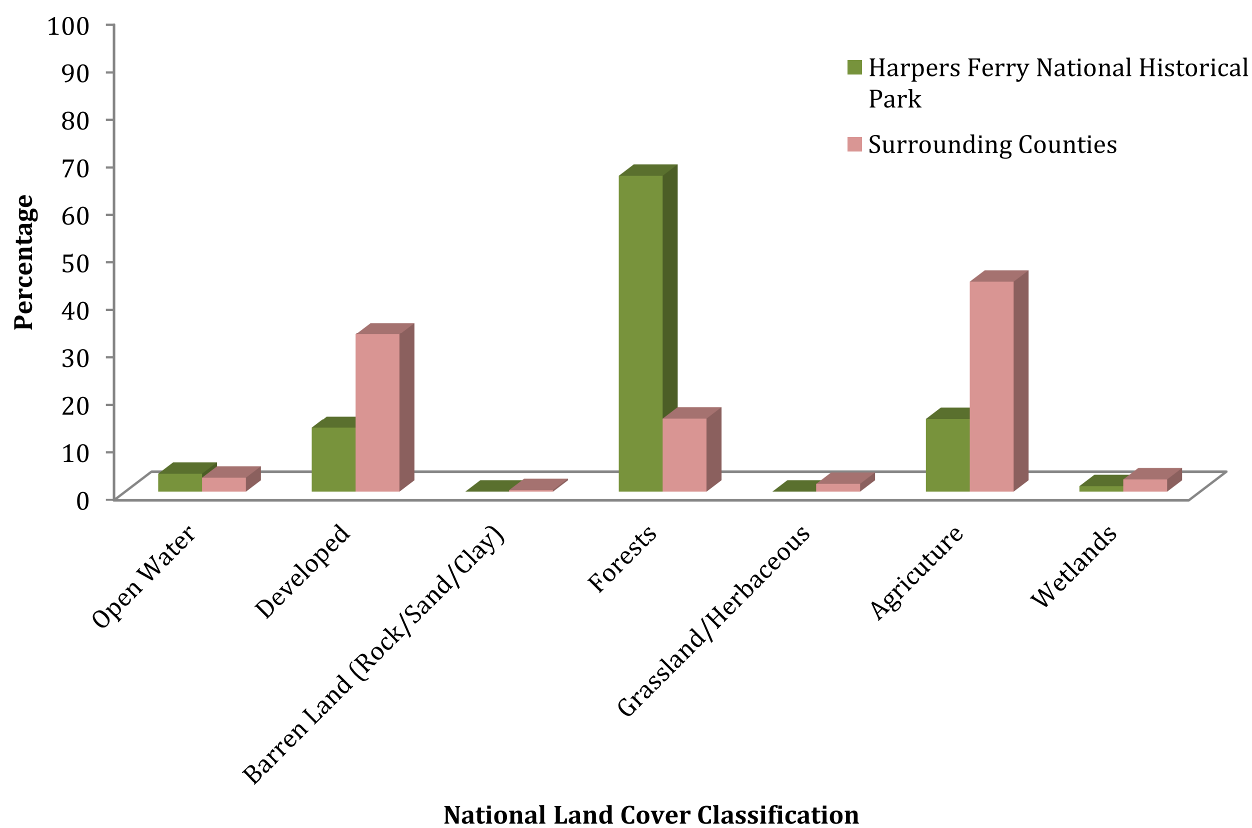

**FIGURE 24: COMPARISON OF LAND COVER TYPES: CHESAPEAKE AND OHIO CANAL NATIONAL HISTORICAL PARK**

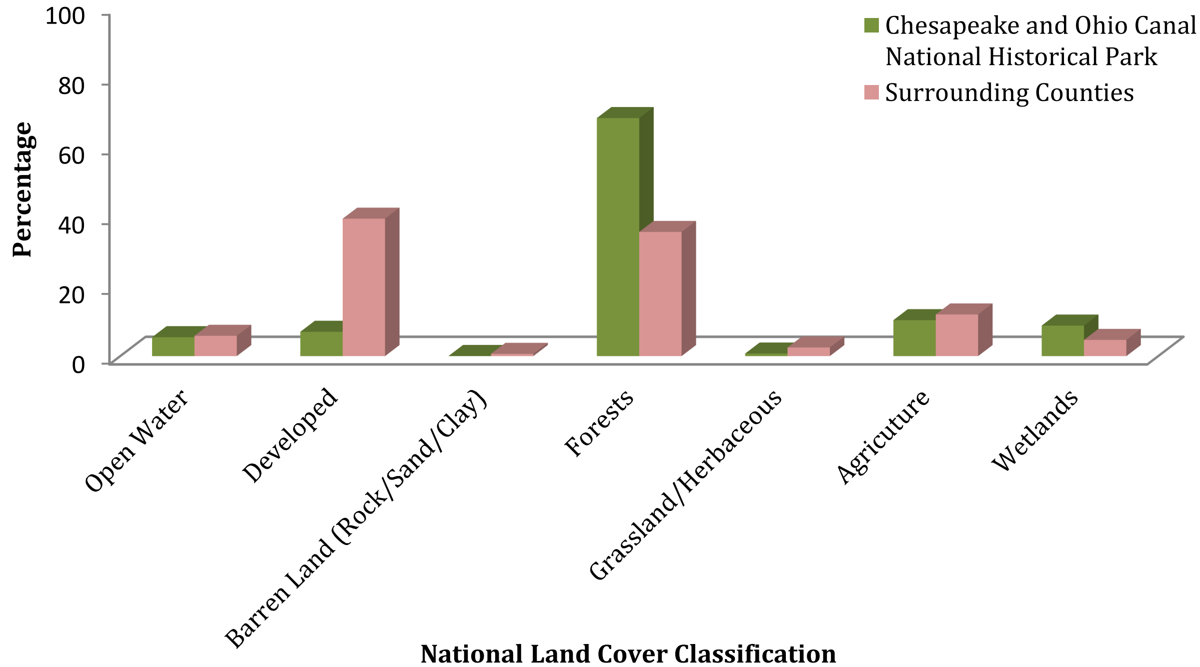


**FIGURE 25: COMPARISON OF LAND COVER TYPES: SHENANDOAH NATIONAL PARK**

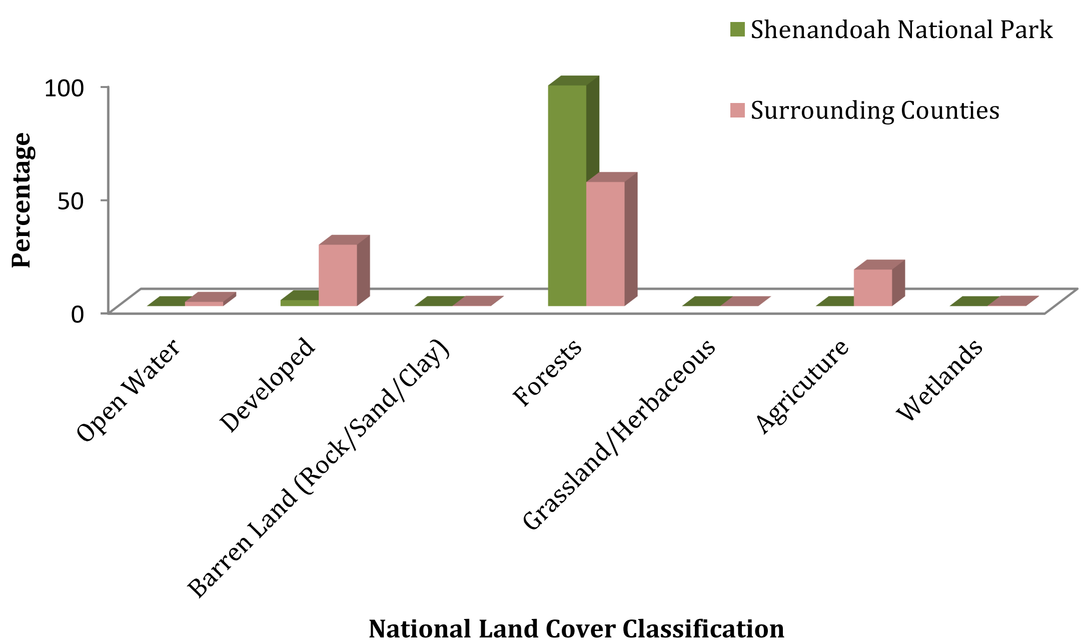

**FIGURE 26: COMPARISON OF LAND COVER TYPES: BLUE RIDGE PARKWAY**

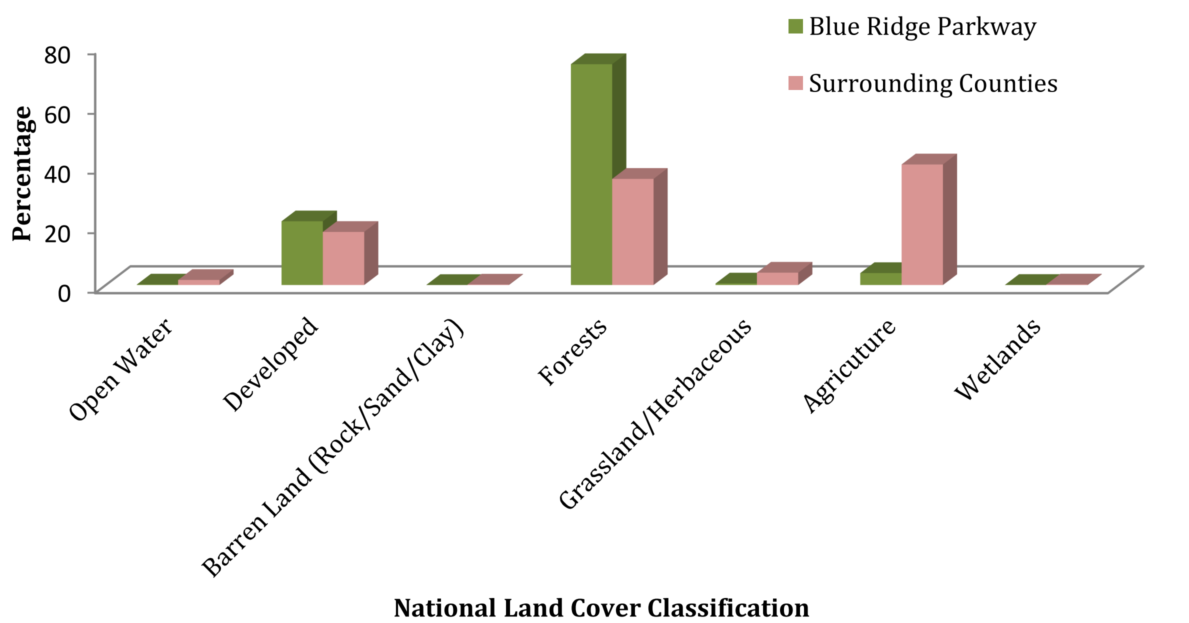


**FIGURE 27: COMPARISON OF LAND COVER TYPES: GREAT SMOKY MOUNTAINS NATIONAL PARK**