# FUTURE LYME DISEASE RISK IN THE SOUTHEASTERN UNITED STATES BASED ON PROJECTED LAND COVER

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ABSTRACT

Lyme disease is the most significant vector-borne disease in the United States. Its southward advance over the last several decades has been quantified, and previous research has examined the potential role of climate change on the disease's expansion, but no research has considered the role of future land cover patterns upon its distribution. This research examines Lyme disease risk in the southeastern United States based on estimated land cover projections under four different Intergovernmental Panel on Climate Change Special Report Emissions Scenarios (IPCC-SRES) A1B, A2, B1, and B2. Results are aggregated to census tracts which are the basic unit of analysis for this study.

This study applied previously established relationships between Lyme disease and land cover in Virginia to the projected land cover layers under each scenario. The study area, the southeastern United States, was defined from Level III Ecoregions that are present in Virginia and extend throughout the Southeast. Projected land cover data for each scenario were obtained from the USGS. The projected land cover datasets are compatible with the National Land Cover Dataset (NLCD) categories and had seventeen land cover categories. The raster datasets were reclassified to four broad land cover types: Water, Developed, Forest, and Herbaceous areas and the relationship between certain landscape configurations were analyzed using FRAGSTATS 4.2.

Significant variables established in previous research were used to develop a spatial Poisson regression model to project Lyme disease incidence for each decade to the year 2100. Results indicated that potential land cover suitability for Lyme disease transmission will increase under two scenarios (A1B & A2) while potential land cover suitability for Lyme disease transmission was predicted to decrease under the other two scenarios (B1 & B2). Total area under the highest category of potential land cover suitability Lyme disease transmission was calculated for each year under each scenario. The A2 scenario experiences the most rapid acceleration of potential land cover suitability for Lyme disease transmission, with an average increase of 16,163.95 $km^2$ per decade, while the A1B scenario was projected to show an average increase of 3,458.47 $km^2$ per decade. Conversely, the B1 scenario showed an average decrease of 595.7 $km^2$ per decade and the B2 scenario showed the largest decrease of potential land cover suitability for Lyme disease transmission with an average decrease of 2,006.83 $km^2$ per decade.

This study examined the potential spatial distribution of potential land cover suitability for Lyme disease transmission in the southeastern United States under four different future land cover scenarios. The results indicate geographic regions of the study area that are at greatest risk of potential land cover suitability for Lyme disease transmission under four different predictive scenarios developed by the IPCC. The A1B and A2 land cover projections are predicted to have

an overall increase in areas where the Lyme disease transmission cycle will be enhanced by 2100 and the scenarios have a primary focus on economic development. Economic concerns outweigh environmental concerns for the A1B scenario, in addition to a high standard of living. The A2 scenario describes rapid population growth which results in high rates of land cover conversion to developed land; in addition, this scenario describes a reduction of environmental protection. The B1 and B2 land cover projections are predicted to have an overall decrease in areas of high Lyme disease transmission by 2100 and these scenarios have a central focus on environmental sustainability. The B1 scenario is characterized by a high environmental awareness which results in lower demand for forest products. A common theme for the B1 scenario is restoration and forest protection. Finally, the B2 scenario is described as improving local and regional environmental value which results in a high demand for biofuels and repossession of degraded lands, and an overall increase of forest cover. This study was the first to predict potential land cover suitability for Lyme disease risk and geographic distribution using projected land cover in the southeastern United States, and the results of this research can aid in the reduction of Lyme disease as it continues to expand in the south.

GENERAL AUDIENCE ABSTRACT

Lyme disease is the most significant vector-borne disease in the United States, recognized for its southward advance over the past several decades. Previous research has examined the potential role of climate change on the disease's continued expansion at the northern extent of its distribution, but no studies have considered the role of future land cover scenarios upon its southward advance, despite a strong association between land cover and Lyme disease emergence. This research examines potential land cover suitability for Lyme disease transmission under projected land cover scenarios provided by the United States Geological Survey under four Intergovernmental Panel on Climate Change Special Report Emissions Scenarios: A1B, A2, B1, and B2. Based on previous research completed in Virginia, developed and herbaceous land cover, and the edges between both herbaceous and forested land in addition to the edges between herbaceous and developed land are all statistically associated with human Lyme disease occurrence. We use a similar statistical model developed in the previous research to quantify potential land cover suitability in the same level III ecoregions present in Virginia projected to their full extent to the south under different land cover scenarios in decadal increments from 2020 to 2100. Results demonstrated variation in potential suitable land cover for Lyme disease transmission depending on the specific scenario. Broadly, if future land cover patterns follow the A1B or A2 scenarios, an increase of suitable areas are to be expected for the Lyme disease transmission cycle. Conversely, if future land cover patterns follow the B1 or B2 scenarios, a decrease of suitable areas are to be expected for enhanced Lyme disease transmission. The results of this research can provide information to public health officials in these areas as the disease continues to expand to the south in the following decades.

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# ATTRIBUTION

Dr. Korine Kolivras is my academic advisor and committee chair. Her experience and expertise in Medical Geography assisted in development and completion of this research in addition to her professional knowledge of Lyme disease. She aided in the writing process and the analysis of the results.

Dr. Yili Hong is a research team member from the Statistics department. He performed the statistical analyses and assisted in generating the tables and figures that were required to complete the research.

Dr. Valerie Thomas is my committee member from the Forest Resources and Environmental Conservation department. Her expertise in forestry and forest structure and Geographic Information Systems was beneficial to the completion of this thesis.

Dr. James Campbell is my committee member from the Geography department. Background in land use and land cover change as well as developed knowledge about Lyme disease research based on co-authorship on previous publications.

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# CHAPTER 1: PROBLEM STATEMENT

## 1.1 Introduction

### 1.1.1 Emerging Infectious Diseases

Emerging infectious diseases are diseases that have newly appeared in a population or have experienced an expansion in the geographic range (Morse, 1995). One of the earliest examples of emerging infectious diseases was derived from the discovery of the cholera bacterium in stool by Gabriel Pouchet in 1849 (Bulloch, 1938). Furthermore, John Snow developed cholera epidemiological maps in which Snow identified the clustering of cholera deaths in relation to the Broad Street water pump, which led to the removal of the pump handle and identification that cholera is a water-borne disease (Meade & Earickson, 2000).

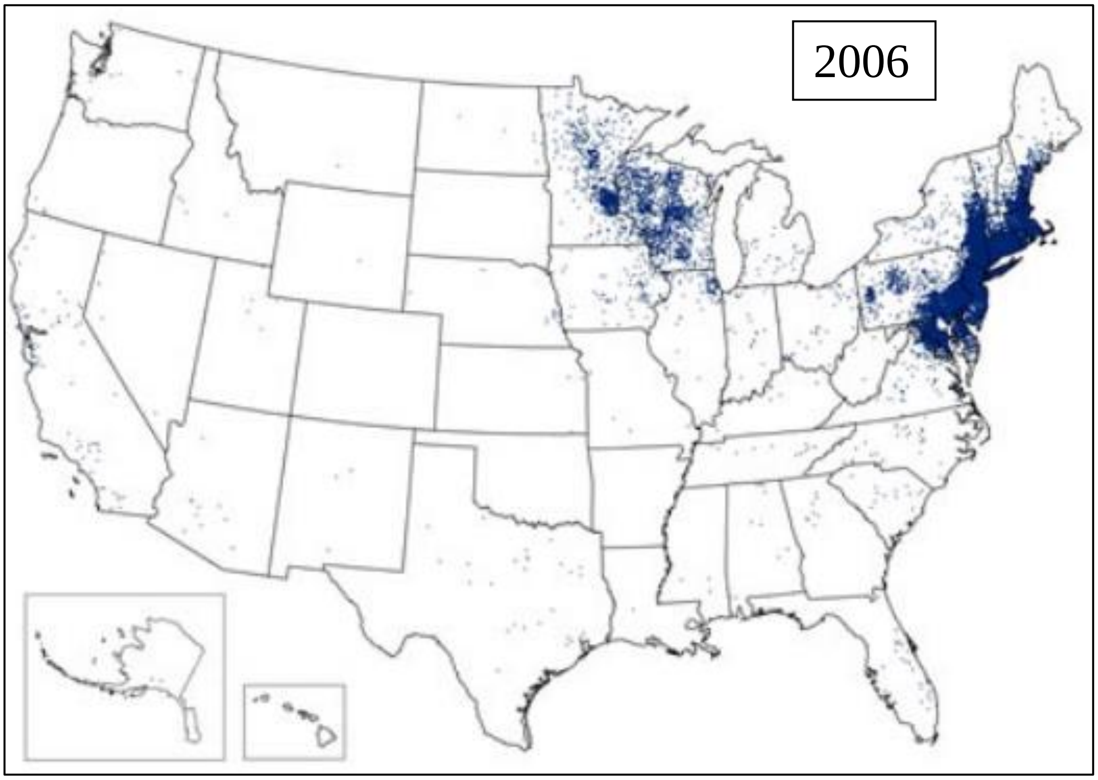
Morse (1995) analyzed specific factors such as ecological, environmental, or demographic variables that can cause infectious diseases to emerge into new places. Emerging infectious diseases can be viewed in the literature as a two-step process: introduction of the agent into a new host population, then establishment and further distribution within the population (Morse, 1995). When one of these two factors is encouraged by a factor, the disease will be inclined to expand. For example, demographic factors such as economic conditions that promote mass migrations of people to new areas encourage disease distribution (Morse, 1995). Ecological and environmental factors contributing to emerging infectious diseases usually occur by the placement of people in relation to a natural reservoir or host for an infection, or by increasing vicinity or changing conditions to favor disease transmission (Morse, 1995). Lyme disease is an example of the outcome of changing ecological and environmental factors of emerging infectious diseases, since suburbanization and reforestation are primarily responsible for the emergence of Lyme disease.

Vector-borne diseases, caused by pathogens transmitted by another living thing, account for 17% of all infectious diseases worldwide, causing more than 700,000 deaths every year (World Health Organization, 2017). Examples of vector-borne diseases include malaria, West Nile virus, typhus, plague, and Lyme disease. Lyme disease has been identified in 38 countries around the world ("IAMAT | Lyme Disease," 2016) and is the most common vector-borne disease in Europe and the United States (CDC, 2016; EEA, 2016). There are 30,000 cases of Lyme disease reported each year in the United States. However, researchers estimate around 300,000 cases go unreported each year due to case misclassification and healthcare provider underreporting (CDC, 2015 & White et al., 2016). Examining the competence of a vector entails an understanding of the biology and ecology of the particular vector. For example, for mosquito-borne disease transmission capability, flight range, elevation range, and breeding grounds are a few characteristics for efficient disease transmission from mosquitos (Meade & Earickson, 2000). As for tick-borne disease transmission efficacy, average winter or summer temperatures, humidity, tick size, elevation, and latitude are a few of the environmental variables that drive the Lyme disease vector, the blacklegged tick (Ginsberg et al., 2017; Khatchikian et al., 2012).

Lyme disease is caused by the bacterium *Borrelia burgdorfer*i, which is transmitted by the bite of a blacklegged tick (*Ixodes scapularis*) in the eastern United States. The disease can cause fever, fatigue, muscular aches, and a distinguishing circular skin rash called, *erythema migrans* (CDC, 2016). Moreover, if left untreated, the disease can cause debilitating side effects if it spreads to other parts of the body, affecting joints, the heart, and the nervous system (CDC, 2016).

Most Lyme disease cases (~95%) in the United States are contracted along the East coast and in the upper Midwest, however, the vast majority (~90%) of Lyme disease cases in those two regions are contracted along the East coast (CDC, 2017; Lantos et al., 2015). Environmental factors impact the distribution of many diseases, including Lyme disease. Several studies have been completed regarding the northern distribution of Lyme disease in North America (Cheng et al., 2017; Ogden et al., 2006; Simon et al., 2014). For example, Simon et al. (2014) predicted a northeastern shift of Lyme disease distribution along the St. Lawrence River by eleven kilometers per year. In northern latitude regions, warmer temperatures as a result of climate change drive diseases to expand their current distribution to allow vector-borne diseases to emerge into new areas (Simon et al., 2014). In 2004, there were only forty cases of Lyme disease in Canada, but as of 2016, the number had grown to 343 cases in Ontario alone (Cheng et al., 2017). The use of climatic models combined with temperatures and moisture needs of the animals involved in the transmission cycle provides estimates of future distributions of Lyme disease. For example, a Canadian study on the northern limit of Lyme diseases distribution predicts a 3.5 kilometer shift northward each year for the disease based on climatic models (Simon et al., 2014).

In addition, Lyme disease is also advancing at the southern edge of its range. A study completed in Virginia, showed the southward expansion of Lyme disease over the study period 1998-2011 with a total of 6,714 cases. Most noteworthy is that 74% of the total cases identified were contracted in the last five years of the study period (Li et al., 2014). Although the disease's approximate range currently ends near the border of North Carolina and Virginia (Figure 1), the disease is likely to continue its southward expansion, given that five counties in North Carolina have met clinical surveillance criteria for Lyme disease since 2009 (Lantos et al., 2015). In addition, the extent of the white-footed mouse and the blacklegged tick are present in these areas, so as the disease continues its southward advance, the Lyme disease transmission cycle will continue to occur. The current extent of the white-footed mouse is southern New England, Mid-Atlantic, and several southern states; it is also found in midwestern states as well as parts of the western states (CDC, 2012). The current extent of the blacklegged tick is fairly similar to that of the white-footed mouse. The blacklegged tick distribution encompasses all of the east coast as well as the southern and midwestern states  and the blacklegged tick is also present in the upper Midwest (CDC, 2010). Although the extent of the white-footed mouse and the blacklegged tick is broad and substantially overlap, the current expanse of Lyme disease along the east coast remains throughout New England to northern North Carolina; and as the disease continues to expand southward, the transmission cycle will still be present in the southeastern United States.



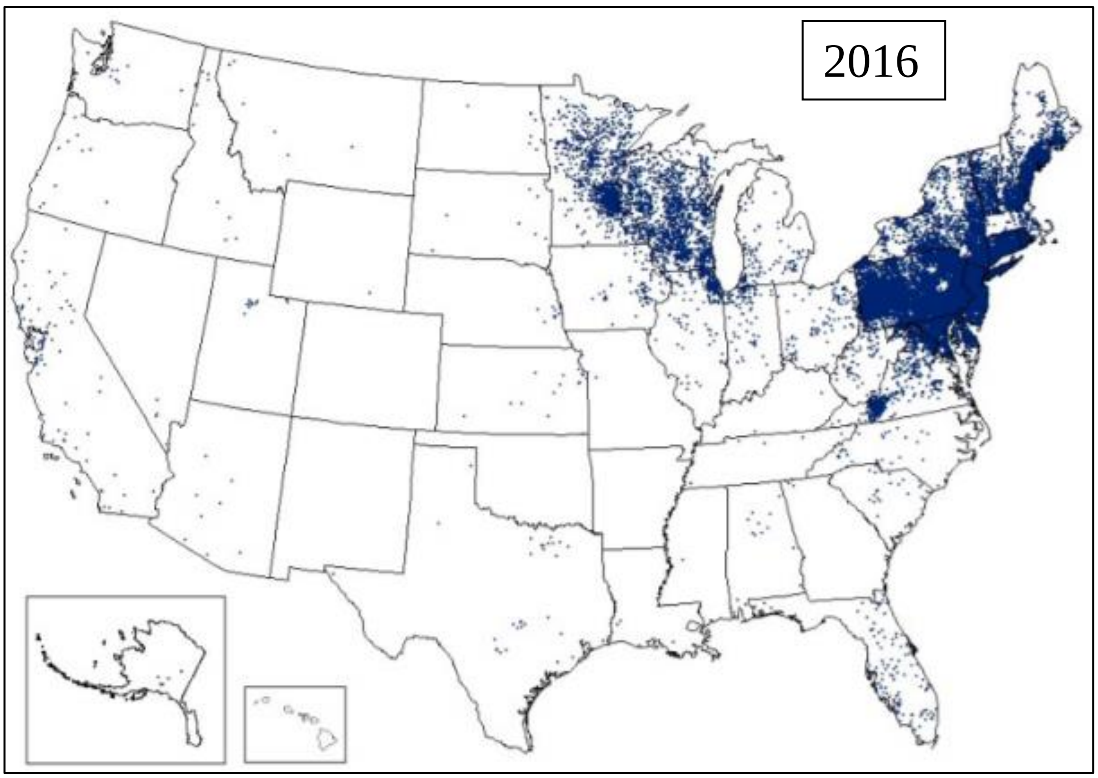




Figure 1.1: Reported Lyme disease cases in the United States for 2006 (top) and 2016 (bottom). Retrieved from CDC, 2017.

## 1.2 Treatment & Prevention Methods

There are several ways for personal protection against Lyme disease such as wearing light-colored clothing for easy tick observation and keeping pant legs tucked into socks create a barrier to ticks (Clark & Hu, 2008). In addition, a basic self-examination after being in tick-prone areas is a good way to remain free from ticks. Shortly after being bitten by an infected blacklegged tick, infection is not well established in the human host, so if ticks are detected and removed within 36 hours after initial attachment, transmission of the bacteria can be prevented (Clark & Hu, 2008). For household-level protection against Lyme disease, physical landscaping management to reduce suitable tick habitat and create physical barriers to prevent movement of host seeking ticks are a few ways to prevent disease transmission (Eisen, Piesman, Zielinski-Gutierrez, & Eisen, 2012).

A vaccination against Lyme disease was approved in 1998 for use in the United States (Hsia, Chung, Schwartz, & Albert, 2002). However, the vaccine was expensive, costing $61.25 per dose to the pharmacy, and three doses in total are needed at 0, 1, and 12 months to sustain immunity Therefore, the human vaccine was withdrawn from the market in 2002 due to lack of sales (Clark & Hu, 2008; Nadelman et al., 2001; Steere et al., 1998). Treatment for Lyme disease is a course of antibiotics; a 20 day course of antibiotics (500mg of amoxicillin) proved to be successful for 88% of the participants in a study (Luft, 1996).

## 1.3 Problem Statement

TA considerable body of research examines Lyme disease and its emergence and distribution. The literature covers a wide variety of approaches and locations in the United States and elsewhere around the world, including Canada and Europe (Lindgren, Jaenson, & others, 2006; Mysterud et al., 2016; Simon et al., 2014). In Europe, specifically Norway, a study contrasted Lyme disease emergence across different ecosystems (Mysterud et al., 2016). Throughout the literature, specific themes can be identified. Much research has been devoted to understanding the effects of land cover manipulation and tracking Lyme disease spatially over the landscape (e.g., Allan, Keesing, & Ostfeld, 2003; Brownstein, Holford, & Fish, 2003; Seukep et al., 2015; Simon et al., 2014).

Some research has focused on understanding the potential shifts in Lyme disease distribution as a result of climate change, but no attention has focused on the potential continued southward expansion of Lyme disease specifically related to future land cover change. Given the strong association between land cover and Lyme disease, this gap in knowledge is an important obstacle to understanding future advances with Lyme disease distribution. In order to address the potential issue of Lyme disease expansion, the following research questions will be answered:

1. Based on current relationships between Lyme disease and land cover characteristics, how will future land cover configurations affect the distribution of Lyme disease throughout the southeastern United States?
2. Where should public health agencies in the southeastern United States apply Lyme disease control and education efforts in the future based on projected land cover patterns?

The results of the research will contribute to our understanding of the potential direction and ideal environments for Lyme disease's distribution and the magnitude of its continued emergence based on projected land cover in the southeastern United States. Risk maps will inform public health agencies in the study area to improve their understanding of how Lyme disease will potentially spread through future land cover scenarios and assist in the education of the general public living in these areas about how land cover manipulation affects the spread of Lyme disease.

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# CHAPTER 2: THE LITERATURE REVIEW

## 2.1 Introduction

This chapter will review the current literature regarding Lyme disease distribution and place the study within the sub-discipline of medical geography. Additional information on Lyme disease will be discussed along with the potential importance of climate change on Lyme disease risk, given the sensitivity of vector-borne diseases to changing climate conditions. Finally, I will discuss the significance of land cover configuration and change on the spread of Lyme disease.

## 2.2 Medical Geography

This research is grounded within the sub-discipline of medical geography, which is the study of the numerous spatial factors that affect the health of populations around the world. Under medical geography, Rosenberg (2016) placed research within the sub-discipline into two categories: Quantitative/Geographic Information Systems (GIS) research (this study) and qualitative research.

In a report published in the journal Progress in Human Geography, Quantitative and GIS research was further broken down into five topics: geographies of diseases in lower/higher income countries, access to health services, the food-obesity-built environment nexus, health inequalities, and mental health (Rosenberg, 2016, p. 547). An example of using quantitative GIS methods in medical geography regarding vector-borne disease is the geostatistical analysis of the relationship of spatial and temporal distributions of anopheline mosquitoes and malaria using kriging (Gaile & Willmott, 2004), in which kriging assumes the same pattern of variation can be observed at all locations on the surface (ESRI, 2018).

On the other hand, qualitative research in medical geography tackles a broader set of themes and theories than quantitative GIS research (Rosenberg, 2016). An example of incorporating qualitative methods with medical geography is observing mental health. In order to study mental health within a population, it is necessary to know something about the psychology, sociology, and anthropology of the subject, which can involve the use of interviews or focus groups (Gaile & Willmott, 2004).

### 2.2.1 Landscape Epidemiology

The term "landscape epidemiology" was originally devised by Russian parasitologist, Eugeny Pavlovsky, in 1966. Pathogens can use many different pathways to spread from an infected host to an uninfected host (Ostfeld, Glass, & Keesing, 2005) and landscape epidemiology plays a large role in understanding the transmission of vector-borne diseases. Landscape epidemiology describes how the temporal dynamics of host, vector, and pathogen populations interact spatially within a permissive environment (Reisen, 2010, p. 461), and furthermore, can indicate the ways in which landscape modification can permit or control disease transmission.

Lyme disease can best be studied through the theoretical framework of landscape epidemiology since landscape configuration is strongly associated with Lyme disease emergence, and it is therefore employed in this study. Lyme disease will likely continue to spread as populations decentralize and neighborhoods are established in wooded areas and agricultural fields that are unintentionally converted to support deer and rodent populations along with human populations (Meade & Earickson, 2000).

Spatial modeling and GIS are important techniques typically employed when using landscape epidemiology as a research framework. Maps have been used to integrate retrospective analyses of spatiotemporally dynamic epidemics to understand what factors govern the spatial pattern and rate of spread of diseases and to characterize spatial variation in static ecological risk of infection and potential causes of that variation (Ostfeld et al., 2005, p. 329). Using a GIS allows the user to provide different variables regarding environmental factors that affect the dispersion of diseases and analyze the patterns to understand how these diseases spread. In particular, vector-borne disease researchers can utilize geographic information on vector, reservoir, and human interaction which can be incorporated with vegetation, topography, soil type, and other environmental and also demographic factors to aid in the explanation and prediction of the distribution of vector-borne diseases (Kitron, 2001).

2.3 Lyme Disease Reservoir and Host

The blacklegged tick's two-year lifecycle is relatively complex (Figure 2), and in order to continue its lifecycle, the blacklegged tick must have a blood meal before each stage of its lifecycle (CDC, 2011). Adult females can lay up to 10,000 eggs in the spring (Meade & Earickson, 2000), and those eggs hatch into larva in the summer. The larval tick's blood meal is usually obtained from a rodent or other small animal, and at this stage, the tick can potentially contract the *B. burgdorferi* bacterium from an infected reservoir (Steere, Coburn, & Glickstein, 2004). The tick will not be active again after its first blood meal until the following spring when it reaches the nymph stage (CDC, 2017). While feeding at the nymph stage, the tick may be infectious if that tick acquired *B. burgdorferi* during a previous bloodmeal. Nymphs will molt into the adult stage in the fall when they will take their final bloodmeal, potentially transmitting the bacterium, and adult ticks will

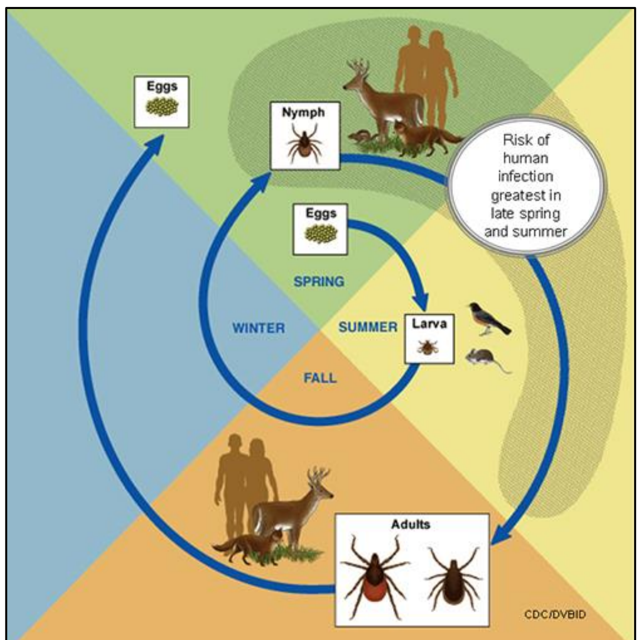


Figure 2.1: Life cycle of the blacklegged tick (CDC, 2011)

mate on large animals such as deer, with the possibility of being transported relatively long distances. Female ticks will lay their eggs on the ground during the following spring, which completes the tick's lifecycle (CDC, 2017).

A reservoir is the source of the infectious agent for the vector. The white-footed mouse is the most efficient reservoir for *B. burgdorferi* along the eastern United States as an infected mouse infects up to 90% of feeding larval ticks (Simon et al., 2014). Lyme disease risk tends to be elevated in forest fragments due to vector-reservoir interactions (Allan, Keesing, & Ostfeld, 2003). Small patches of forest results in less biodiversity, i.e., fewer small mammals, and fewer predators to the white-footed mouse, so if a tick feeds on a mammal inside a forest fragment, it is more likely to be a white-footed mouse. More specifically, a decrease in the size of forest patches was found to contribute to a higher number of white-footed mice (Yahner, 1992), which is the primary reservoir to Lyme disease. Other competent Lyme disease reservoirs include a variety of animals. For example, eastern chipmunks and American robins are moderately efficient reservoirs in North America (Ostfeld & Keesing, 2000), while the black striped mouse, bank vole, and sand lizard are Lyme disease reservoirs in Europe (Matuschka, Fischer, Heiler, Richter, & Spielman, 1992). However, these reservoirs are not as competent as the white-footed mouse for disease transmission.

### 2.3.1 White-Footed Mouse – A Reservoir for *B. burgdorferi*

In a study completed in Massachusetts, ticks were removed from 236 white-footed mice, and an average of 4.2 nymphs were found on each white-footed mouse and half of the collected ticks were infected with the bacterium; essentially all mice sampled in the study were infected with the Lyme disease bacterium (Wilson, Levine, & Spielman, 1985). In Europe, the vector for Lyme disease is *Ixodes dammini* and similar testing was done on potential reserviors. In this case, four species of animals were tested: black-striped mice, yellow-necked mice, bank voles, and sand lizards. Matuschka et al. (1992) hypothesized that ticks feast on rodents more often than other animals because their home range is larger and they spend less time in one particular place, so rodents largely come in contact with ticks while they forage on the forest floor.

2.3.2 White-Tailed Deer – A Host for *I. scapularis*

A host is any living thing harboring an infectious agent and the white-tailed deer are the primary host animals for ticks; ticks mate on deer and deer are a source of bloodmeals for ticks. Amerasinghe et al. (1992) collected 3,437 ticks from 1,281 hunted deer carcasses throughout Maryland, with collection area classified by its physiographic region, and found a maximum infection rate of ticks of 21% with an average infection rate of 8% in the early beginnings of Lyme disease research in 1992. White-tailed deer provide a bloodmeal and mode of transportation for adult blacklegged ticks, relocating them into new areas. In addition, forest fragmentation provides more forest-edge environments in which white-tailed deer thrive, than in intact forests (Brownstein, Skelly, Holford, & Fish, 2005).

In suburban areas where hunting is essentially non-existent, deer populations tend to rapidly increase (Brownstein et al., 2005), which will likely increase the prevalence of Lyme disease in those areas due to the landscape configuration of suburban areas. Since white-tailed deer are important to tick survival and for Lyme disease transmission, deer control has been attempted to reduce the amount of feeding ticks. The U.S. Department of Agriculture attempted to render all deer incapable of serving as a tick host through acaricide treatment (a pesticide that kills ticks) via a corn bait and roller system near the Mexican border to attempt to eradicate Rocky Mountain spotted fever – another tick-borne illness (Fish & Childs, 2009). The corn bait and roller system developed by the Tick Fever Eradication Program proved to be highly effective in the control of *Ix. Scapularis* using white-tailed deer as a host. The experiment was successful, however, after removal of the system, tick populations rebounded; long-term maintenance costs and other considerations limited the success of the device (Wong et al., 2018).

## 2.4 Effects of Climate on Lyme Disease Distribution

Climate variability has an impact on Lyme disease incidence. Annual Lyme disease incidence is positively correlated with a summer moisture index represented by Palmer Hydrological Drought Index (PHDI), as an increase in precipitation can increase the number of breeding sites for ticks in North America (Githeko, Lindsay, Confalonieri, & Patz, 2000). In addition, Subak (2003) found three climate variables associated with Lyme disease incidence: PHDI during the same year, warmer winter temperatures during the previous year, and PHDI two years prior. Generally, the study specifies a positive relationship between moisture levels two years prior to the study year, in addition to drought conditions that inhibit immature tick survival (Subak, 2003). Additionally, in an unpublished paper, a model was used to examine the relationship between climate and Lyme disease incidence in Virginia. The results of this study found temperatures from the previous spring, number of days with temperatures greater than 8°C, number of days with a minimum temperature between -11°C and -7°C, number of extreme cold days during the current spring, winter and spring precipitation in the current year were all significantly correlated with Lyme disease incidence rate (Zhao, 2016). Additionally, the climate in the southeastern United States would support the Lyme disease transmission cycle as the blacklegged tick thrives in warmer, and humid environments to allow the blacklegged tick a longer timeframe to contract and transmit the pathogen (Levi, Keesing, Oggenfuss, & Ostfeld, 2015). Furthermore, Levi et al. (2015) identified climatic warming over a nineteen-year study period resulted in advanced phenological activity of larval and nymphal ticks.

Ogden et al., (2006) projected the potential range of Lyme disease at the northern limit of its current distribution in Canada. This study utilized two Global Climate Models for two Intergovernmental Panel on Climate Change (IPCC) emission scenarios to model the northward spread of tick populations. This study found that the B2 scenario, which projects a reduction in emissions, had little effect on *Ix. scapularis*' northward distribution until 2050, while under the A2 scenario, driven by projected annual temperature, tick abundance nearly doubled by the 2020's at the northern limit of *Ix. scapularis*' distribution (Ogden et al., 2006).

## 2.5 Effects of Land Cover Configuration on Lyme Disease Risk

Land cover characteristics and landscape configuration have an effect on the spread of Lyme disease. Specifically, forest fragmentation which is the breakup or reconfiguration of a contiguous forested area often due to urban/suburban development and from the development of agricultural fields provide ideal environments for Lyme disease transmission. The diversity of small mammals is influenced by forest fragmentation, which in turn impacts the source of a bloodmeal for immature ticks (Eisen, Piesman, Zielinski-Gutierrez, & Eisen, 2012).

Landscape fragmentation provides ideal edge-environments in which the white-tailed deer and white-footed mice thrive (Allan et al., 2003; Seukep et al., 2015; Tran & Waller, 2013). Also, smaller forest fragments maintain an abundance of small mammals (e.g. white-footed mice) which serve as the host for immature ticks (Brownstein et al., 2005). Agricultural fields are of concern due to the creation of forest fragments by converting forested areas to patches of cultivated fields, which generates additional forest-herbaceous edge environments. Forest fragmentation in suburban and agricultural environments poses the ideal environment for Lyme disease hosts and reservoirs since the forest-herbaceous edge, longer in a fragmented environment, was one of several variables found to be significantly positively correlated with Lyme disease incidence in Virginia (Seukep et al., 2015).

Landscapes that contain a large percentage of forest-herbaceous edge environments were found to be statistically the strongest correlated variable with Lyme disease rates in Maryland (Jackson, Hilborn, & Thomas, 2006). The findings in Jackson et al. (2006) demonstrate the effectiveness of a movement towards designing landscapes to aid in the prevention of Lyme disease transmission. Furthermore, Seukep et al. (2015) found that percent developed land was negatively correlated with incidence rate due to the lack of ideal environments for Lyme disease host and reservoir interaction. However, Seukep et al. (2015) found percent herbaceous land was significantly positively correlated with Lyme disease incidence in Virginia. Jackson et al. (2006) found percent forested areas to be positively correlated with incidence while alternatively, Seukep et al. (2015) did not find percent forested area to be a significant variable in Lyme disease risk. Those results may be explained by the presence of large areas of undisturbed forested regions in Virginia, while intact forest cover in Maryland is relatively scarce (Seukep et al., 2015).

In addition, Horobik et al. (2007) found that a higher level of edge environments resulted in a higher risk of Lyme disease prevalence among animals inside the forest patches' interior. Jackson et al. (2006) studied Lyme disease emergence in Maryland and found with every 10% increase in the forest edge-contrast index corresponded with a 34% increase in Lyme disease incidence rate; the forest edge-contrast index explained the most variability in incidence. White-tailed deer, the primary host animal and breeding ground for ticks, provide the spatial redistribution and new generation relocation for ticks (Roome et al., 2017). This is particularly concerning because white-tailed deer thrive in forest-edge environments, which have the potential to overlap with ideal white-footed mouse environments (Seukep et al., 2015; Yahner, 1992).

## 2.6 Conclusion

Lyme disease continues to be a growing problem in the United States, as it is most prevalent along the East Coast, but Lyme disease has been reported in all 50 states (LDA, 2018). Landscape epidemiology suggests that landscape modification is a key factor in the control of diseases, and as people modify the landscape, areas supportive of the Lyme disease transmission cycle are developed. While we understand links between Lyme disease and land cover configuration, there has been no research completed regarding the projected future distribution of Lyme disease in the southeastern United States using future land cover scenarios. It is important to predict where the disease will spread in the coming decades as it continues to emerge so public health officials can properly prepare for Lyme disease outbreaks as it continues its southward expansion. If we understand the important factors that contribute to Lyme disease's distribution, we can inform public health agencies and local governments as to when and where Lyme disease is likely to occur across the region.

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# Chapter 3:

# Future Lyme Disease Risk in the Southeastern United States Based on Projected Land Cover

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Abstract

Lyme disease is the most significant vector-borne disease in the United States, and its southward advance over the past several decades has been recognized and quantified. Previous research has examined the potential role of climate change on the disease's continued expansion, but no studies have considered the role of future land cover patterns upon its distribution, despite strong association between land cover and Lyme disease emergence. This research examines Lyme disease risk in the southeastern United States based on projected land cover developed under four Intergovernmental Panel on Climate Change Special Report Emissions Scenarios: A1B, A2, B1, and B2. Based on research previously completed in Virginia, developed and herbaceous land cover, and edges between both herbaceous and forested land and between herbaceous and developed land are all significantly associated with human Lyme disease occurrence. We incorporated these variables into a spatial Poisson regression model to quantify potential land cover suitability for Lyme disease under the four scenarios. Results indicated a rapid intensification of potential land cover suitability for Lyme disease transmission under the A2 and A1B scenarios, while a decrease of potential land cover suitability for Lyme disease transmission is projected to occur under the B1 and B2 scenarios. Public health officials can use this information to consider applying surveillance and education efforts related to Lyme disease in the projected high incidence areas.

Keywords:
Lyme Disease, Medical Geography, GIS, Spatial Poisson Regression, Land Cover

## 3.1 Introduction

Lyme disease, the most common vector-borne disease in the United States (Centers for Disease Control and Prevention, 2016), is caused by the bacterium *Borrelia burgdorferi*, which is transmitted to humans through the bite of a blacklegged tick (*Ixodes scapularis*) in the eastern United States or the western blacklegged tick (*Ixodes pacificus*) in the western United States (Centers for Disease Control and Prevention, 2016). The disease can cause fever, fatigue, muscular aches, and a distinguishing skin rash referred to as, e*rythema migrans* (Centers for Disease Control and Prevention, 2016). In addition, if the disease is left untreated, it can cause debilitating side effects as it can spread to other parts of the body affecting joints, the heart, and the nervous system (Centers for Disease Control and Prevention, 2016). The vast majority (90%) of all Lyme disease cases in the United States are contracted along the East Coast from New England to southern Virginia (Lantos et al., 2015). First identified in the 1970's in New England, the disease's distribution continues to expand as demonstrated in a study completed in Virginia. Lyme disease expanded southward during the study period of 1998-2011 with a total of 6,714 cases (Li et al., 2014). Most noteworthy is that 74% of those cases were contracted in the last five years (Li et al., 2014). Although the disease's approximate range currently ends near the North Carolina border, the disease is likely to continue its southward expansion as five counties in North Carolina have met "clinical surveillance" criteria for Lyme disease since 2009 (Lantos et al., 2015).

There is a considerable body of research that has examined Lyme disease's emergence and distribution. A number of themes can be identified, covering a wide variety of approaches, explanatory variables, and locations in the United States and elsewhere around the world, including Quebec, Canada and Europe (Lindgren, Jaenson, & others, 2006; Mysterud et al., 2016; Simon et al., 2014). More specifically, much research has been devoted to understanding effects of land cover change, estimating potential shifts in Lyme disease distribution as a result of climate change, and tracking Lyme disease spatially over the landscape. There is little research on Lyme disease along the southern extent of the disease's range, and no research has quantified potential Lyme disease distributions based on projected land cover. An understanding of the areas in the southeastern United States that may be characterized by landscape factors known to be correlated with Lyme disease will aid public health officials in those areas as Lyme disease continues to emerge.

Previous studies have quantified the potential future range of Lyme disease under projected climate conditions (Ogden et al., 2006; Simon et al., 2014; Tran & Waller, 2013), but no study has examined potential distributions under projected land cover, which includes variables most strongly associated with Lyme disease emergence. In this study, we quantify the potential continued emergence of Lyme disease in the southeastern United States under four different land cover situations produced using the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES). Specifically, we seek to answer the following research questions:

1. Based on current relationships between Lyme disease and land cover characteristics, how will future land cover configurations affect the distribution of Lyme disease throughout the southeastern United States?
2. Where should public health agencies in the southeastern United States apply Lyme disease control and education efforts in the future based on projected land cover patterns?

Results of this research will therefore contribute to understanding of the potential direction and magnitude of Lyme disease's continued emergence, based on projected land cover. Risk maps will improve public health officials' understanding of how Lyme disease will potentially spread through the region and what processes can be implemented to prevent and control Lyme disease outbreaks. Results of the research can be used to educate the general public living in this region about potential future Lyme disease dissemination.

## 3.2 Background

The blacklegged tick's two-year lifecycle is relatively complex, but understanding the lifecycle is critical to understanding the Lyme disease transmission cycle. The blacklegged tick must have a blood meal before each state of its lifecycle (CDC, 2017), which perpetuates Lyme disease transmission. Adult females lay eggs in the spring, and those eggs hatch into larva in the summer. The larval tick's bloodmeal is usually obtained from a rodent or another small animal; at this stage, the tick can contract *B. burgdorferi* from an infected reservoir. The tick will not be active after its first bloodmeal until the following spring when it reaches the nymph stage (CDC, 2017). While feeding at the nymph stage, the tick may be infectious with the previously acquired *B. burgdorferi* bacterium, at which point the bacterium could potentially be transmitted to a human. Nymphs will then molt into the adult stage in the fall, taking an additional bloodmeal and again, potentially transmitting the bacterium to a human. Adult ticks will typically mate on large animals, such as white-tailed deer, with the potential of being transported relatively long distances, introducing infected ticks to new areas. The adult female ticks will lay their eggs on the ground during the following spring, which completes the tick's lifecycle (CDC, 2017).

Ticks feed on a variety of animals, including birds, reptiles, and amphibians, but the white-footed mouse is the most competent reservoir for the *B. burgdorferi* bacterium. An infected white-footed mouse can infect up to 75-90% of larval ticks (Simon et al., 2014), and these immature blacklegged ticks cause the majority of human infections because of their very small size, by which nymphal ticks latch onto human hosts unnoticed. Throughout the southeastern United States, the blacklegged tick and white-footed mouse habitats overlap substantially, indicating the Lyme disease transmission cycle will progress as the disease continues to expand southward. Other competent Lyme disease reservoirs include a variety of animals. For example, eastern chipmunks and American robins are considered to be moderately efficient reservoirs in North America (Ostfeld & Keesing, 2000), while the black striped mouse, bank vole, and sand lizard are Lyme disease reservoirs in Europe (Matuschka, Fischer, Heiler, Richter, & Spielman, 1992).

Land cover characteristics and configuration can affect spread and incidence of Lyme disease, as those variables impact the density of, and interactions between, hosts, vector, and reservoirs. An abundance of "edge" environments, the boundary between different land cover types, can amplify Lyme disease risk because white-tailed deer, which are the primary host for adult ticks, and white-footed mice, which are the primary host for nymphal ticks, flourish in edge environments (Seukep et al., 2015; Simon et al., 2014). Patchy, fragmented landscapes, which have longer levels of edge environments than contiguous landscapes, support Lyme disease transmission. White-footed mice generally have a higher abundance in smaller forest fragments due to the lack of competition and predators inside forest fragments (Nupp & Swihart, 1996). Since small patches of forest result in lower biodiversity and fewer predators to the white-footed mouse, which thrive in forest patches (Allan, Keesing, & Ostfeld, 2003), a tick feeding inside a small forest fragment is more likely to feed on a white-footed mouse than a less competent reservoir than the white-footed mouse. Horobik et al. (2007) found that a higher level of edge environments resulted in a higher risk of Lyme disease in forest patches' interior in a study of edge environments in southeastern New York. Results of a different study showed that nymphal tick density was three times higher inside the smallest selected forest patches than in larger forest patches greater than 1.2 hectares (Allan et al., 2003, p. 269).

When specifically examining human Lyme disease, anthropogenic changes to the environment have been identified as a contributor to the increase of human Lyme disease (Khatchikian et al., 2012); as suburbanization, reforestation, or other landscape modifications occur, different types of edges between land cover types are created. Forest-herbaceous and herbaceous-developed edge environments were found to be positively and negatively, respectively, associated with Lyme disease in Virginia (Seukep et al. 2015). Moreover, the forest-herbaceous edge, as measured using the edge contrast index, was found to be the most influential characteristic of Lyme disease incidence in Jackson et al.'s (2006) study of Lyme disease emergence in Maryland, with every 10% increase in the value of the edge-contrast index corresponding to a 34% increase in Lyme disease incidence rate. Overall, fragmented forests provide more edge environments in which white-tailed deer thrive and in suburban areas where hunting is essentially non-existent, white-tailed deer populations tend to be high (Brownstein, Skelly, Holford, & Fish, 2005). Therefore, fragmented landscapes support both white-tailed deer and white-footed mouse populations, thereby contributing to human Lyme disease transmission.

## 3.3 Study Area

The current range of human Lyme disease ends roughly near the border of North Carolina and Virginia, and the disease is likely to continue its southward expansion given that five counties in North Carolina have met clinical surveillance criteria for Lyme disease since 2009 (Lantos et al., 2015). The southeastern United States was chosen for this study because there is little to no research to estimate the future spatial distribution of Lyme disease if it continues to expand southward. Seukep et al. (2015) examined environmental and demographic variables that are correlated with Lyme disease in Virginia. This research uses Level III Ecoregions, as defined by the U.S. Environmental Protection Agency, that are present in Virginia and expands them to their full extent in the southeastern United States. Ecoregions represent fairly uniform ecosystems in which to assess Lyme disease risk since Lyme disease distribution is reliant on specific environmental characteristics and conditions to support the various species involved in the Lyme disease transmission cycle. We argue that Lyme disease could potentially exist in the future in those ecoregions where Lyme disease is currently endemic. Figure 3.1 portrays the extent of the study area based on Level III Ecoregions which include the Blue Ridge, Central Appalachians, Middle Atlantic Coastal Plain, Northern Piedmont, Piedmont, Ridge and Valley, and Southeastern Plains ecoregions.

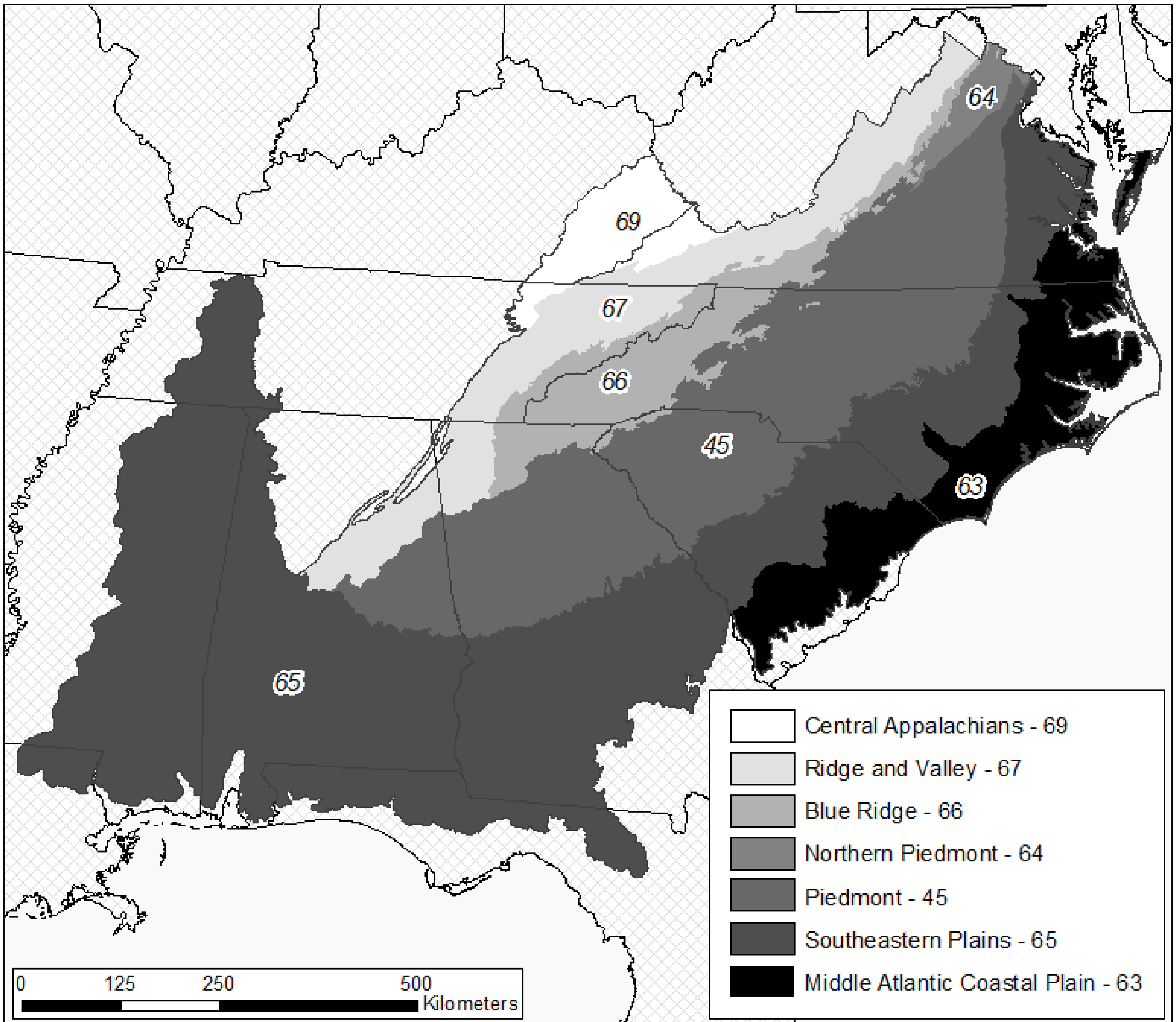



**Figure 3.1:** Study area defined by EPA Level III ecoregions that are present in Virginia

3.4 Data

This research uses projected land cover data provided by the United States Geological Survey (USGS, 2012), in addition to census tract polygons in order to aggregate the results to census tracts. The projected land cover datasets provide spatial and temporal scenarios of land use and land cover from 2020 to 2100 with a spatial resolution of 250 meters. Each raster image contains seventeen land cover classifications that are consistent with the National Land Cover Dataset (NLCD). Seukep et al (2015) found developed, forested, and herbaceous land, in addition to several edge indices, were significant in the distribution of Lyme disease in Virginia, therefore, based on the description of each land cover type provided in the metadata, the seventeen land cover classifications were reclassified into four land cover types: water, developed, forested, and herbaceous cover. Temporally, the data were classified to decadal increments for each scenario beginning with year 2020 through 2100. Table 1 provides the USGS land cover classification, the definition provided by the metadata, and the new land cover classification used in this study.

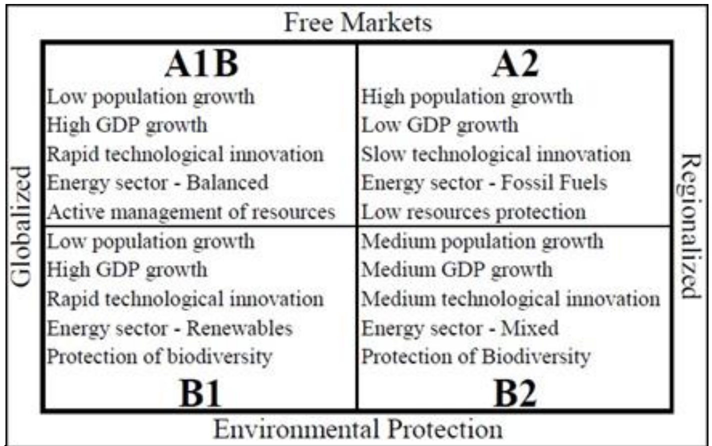



**Figure 3.2**: IPCC-SRES characteristics. Adapted from Sleeter et al. (2012)

The projected land cover scenarios were developed based on historical land cover conditions combined with the IPCC-SRES scenarios A1B, A2, B1, and B2 (USGS, 2012). The IPCC-SRES scenarios represent a wide variety of assumptions related to global versus regional foci for economic, technological, and environmental cooperation as well as emphasis on economic growth versus environmental conservation (IPCC, 2018a; Sleeter et al., 2012a; Figure 3.2); when attempting to project land cover data into the future, it is important to consider several different potential possibilities. The scenarios therefore represent diverse images of how the future can unfold and reflect, as well as possible, the range of uncertainty (IPCC, 2018a).

In further detail, the A1B scenario is part of the "A1 storyline and scenario family" that describes a world with extremely rapid economic growth, rapid population growth that peaks mid-century, and rapid growth of more efficient technologies (IPCC, 2018). The A1B scenario indicates a balance across all energy foci, and it is characterized by strong economic growth, high levels of technological innovation, international mobility of ideas, and technology, and high rates of land use land cover change (Sleeter et al., 2012). Environmental concerns are secondary to economic growth and urban growth is strong in the A1B scenario (Sleeter et al., 2012). This scenario describes an affluent population with a focus on wealth accumulation and the achievement of an opulent lifestyle, which results in high pressure on forest resources, resulting, in turn, in an increase of fragmented landscapes (Sleeter et al., 2012).

The fundamental aspect of the "A2 storyline and scenario family" is self-reliance and preservation (IPCC, 2018). Instead of rapid population growth that peaks mid-century like experienced in the A1B scenario, the A2 scenario describes a continuously increasing population over time; economic and technological growth are primarily regionally-based and increase slower than under the A1B scenario (IPCC, 2018). Large population growth results in the highest rates of conversion of lands for developed uses of the scenarios, with an absence of government regulation to restrict urban sprawl (Sleeter et al., 2012). The A2 scenario also includes a government with little attention to conservation but strong governmental support to maintain overproduction (Sleeter et al., 2012). This scenario focuses little on protecting the environment to instead aid in the demands of a growing population. Logging and forest cutting intensifies with large areas of cropland becoming more common (Sleeter et al., 2012).

The “B1 storyline and scenario family” portrays a convergent world that includes the same rapid global population that peaks mid-century, as in the A1 storyline, but this scenario includes rapid change in economic structures toward a service and information economy with reductions in demand for resources, and this scenario represents the introduction of clean and resource-efficient technologies (IPCC, 2018). This scenario also emphasizes global solutions to economic, social, and environmental sustainability but without additional climate initiatives (IPCC, 2018). This scenario is characterized by technological advancement resulting in higher crop yields; however, productivity increases are balanced against environmental concerns which restrict many intensive farming practices (Sleeter et al., 2012). Objectives of land management in this scenario include attempts to protect biodiversity and water quality, and forestland restoration occurs marginally (Sleeter et al., 2012).

Finally, the “B2 storyline and scenario family” depicts a world where the emphasis is focused on local solutions to economic, social, and environmental sustainability (IPCC, 2018). This scenario describes a continuously growing population at a rate lower than the A2 scenario, and intermediate levels of economic development with less rapid but more diverse technological change (IPCC, 2018). The B2 scenario is concerned with environmental protection and social equality on local levels (IPCC, 2018). This scenario is marked by gradual changes and less extreme developments (Sleeter et al., 2012). Low population growth results in a societal focus on environmental sustainability (Sleeter et al., 2012). Food security becomes a concern in this scenario which results in a shift of dietary patterns towards local products and reduced meat consumption (Sleeter et al., 2012). Forested area remains stable due to the overall demand for biofuels (Sleeter et al., 2012).

**Table 3.1:** USGS land cover classification, USGS definition of land cover, and reclassified land cover categories in ArcGIS 10.5

| USGS Land Cover Type & Categorical Code | USGS Description of Land Cover Type (USGS, 2012) | Reclassified Categories |
|---|---|---|
| Water (1) | Areas of open water, generally with less than 25% vegetation/land cover. | Water (1) |
| Developed (2) | Areas characterized by a high percentage (20% or greater) of constructed material (concrete, asphalt, buildings, etc.) | Developed (2) |
| Mechanically Disturbed National Forest (3) | Forested lands within National Forests that have been mechanically disturbed (cleared, thinned, etc.) | Forest (3) |
| Mechanically Disturbed Other Public Land (4) | Forested lands within all other publicly owned property (excluding National Forests) that have been mechanically disturbed (cleared, thinned, etc.) | Forest (3) |
| Mechanically Disturbed Private Land (5) | Mechanically disturbed (cleared, thinned, etc.) forested lands on privately-owned property. | Forest (3) |
| Mining (6) | Areas of extractive mining activities with surface expressions | Developed (2) |
| Barren (7) | Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no "green" vegetation present regardless of its inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the green vegetated categories; lichen cover may be extensive | Developed (2) |
| Deciduous Forest (8) | Areas dominated by trees where 75% or more of the tree species shed foliage simultaneously in response to seasonal change | Forest (3) |
| Evergreen Forest (9) | Areas dominated by trees where 75% or more of the tree species maintain their leaves all year. Canopy is never without green foliage | Forest (3) |
| Mixed Forest (10) | Areas dominated by trees where neither deciduous nor evergreen species represent more than 75% of the cover present | Forest (3) |
| Grassland (11) | Areas dominated by grasses and forbs. In rare cases, herbaceous cover is less than 25%, but exceeds the combined cover of the woody species present. These areas are not subject to intensive management, but they are often utilized for grazing. | Herbaceous (4) |
| Shrubland (12) | Areas dominated by shrubs; shrub canopy accounts for 25 to 100% of the cover. Shrub cover is generally greater than 25% when tree cover is less than 25%. Shrub cover may be less than 25% in cases when the cover of other life forms (e.g. herbaceous or tree) is less than 25% and shrubs cover exceeds the cover of the other life forms | Herbaceous (4) |
| Cropland (13) | Areas dominated by vegetation that has been planted or is intensively managed for the production of food, feed, or fiber; or is maintained in developed settings for specific purposes. Includes cultivated crops, row crops, small grains, and fallow fields | Herbaceous (4) |
| Hay/Pasture (14) | Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops | Herbaceous (4) |
| Herbaceous Wetland (15 | Areas where perennial herbaceous vegetation accounts for 75% to 100% of the cover and the soil or substrate is periodically saturated with or covered with water. | Herbaceous (4) |
| Woody Wetland (16) | Areas where forest or shrubland vegetation accounts for 25% to 100% of the cover and the soil or substrate is periodically saturated with or covered with water | Forest (3) |
| Ice/Snow (17) | Areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover. | Water (1) |

3.5 Methods

Land cover scenario data for each decade were reclassified into the four broad categories using ArcGIS 10.5 (ESRI, 2017) and aggregated to the census tract, which is the basic unit of analysis to assess potential land cover suitability for Lyme disease in the study area for this research. In order to analyze landscape fragmentation, reclassified land cover layers for each decadal period under each of the four scenarios were converted to GeoTIFF, and imported into the fragmentation analysis software, FRAGSTATS 4.2 (McGarigal, Cushman, & Ene., 2012).

The variables found to be statistically significantly associated with Lyme disease in Virginia (Seukep et al., 2015), and used in the analysis presented here, are percent developed land, percent herbaceous land, and indices that measure the edge between forest-herbaceous land and herbaceous-developed land. Land cover percentages in each census tract were calculated in ArcGIS 10.5 using the *Zonal Statistics as Table* tool (ESRI, 2017). After computing the total area of developed and herbaceous land per census tract the total area of the pixels of interest were divided by the total area of the census tract and multiplied by 100 in order to find the percent land cover of interest per census tract.

The specific significant edge variables of interest from Seukep et al. (2015) were the forest-herbaceous edge and the herbaceous-developed edge measured using two contrast metrics: Contrast-Weighted Edge Density (CWED) and Total-Edge Contrast Index (TECI). CWED was calculated for herbaceous-developed land and TECI was calculated for herbaceous-developed and forest-herbaceous edge types in FRAGSTATS 4.2 across the southeastern United States. CWED is the sum of the weighted edge lengths divided by the total area. This measurement finds the total area of the edge between two intersecting land cover types in the corresponding census tract. TECI is a percentage that is computed by summing the edge lengths between two intersecting land cover types and dividing by the total landscape edge length. TECI quantifies edge contrast as a percentage of maximum possible. In order to aggregate the CWED and TECI values to census tracts, we had to perform an exhaustive sampling technique of providing “tiles” to the software. The “tiles” were the census tracts for the southeastern United States. In order to calculate the CWED and TECI in FRAGSTATS 4.2, two weighted matrices for forest-herbaceous edge and herbaceous-developed edge were created and imported into the software. Each matrix weighted the land cover edges of interest a value of one and the other types zero.

A spatial Poisson regression model was developed using the five variables described previously in Seukep et al. (2015) to generate predicted annual incidence rates for each census tract (n = 9872) for each scenario for each decadal time period through 2100(e.g., at year 2020, year 2030, etc.). The model was created in a similar manner to the model in Seukep et al. (2015). A spatial Poisson regression model is appropriate for this research due to the nature of the data being integer-valued from estimating Lyme disease cases, and Poisson regressions are commonly used for analyzing disease case data (Torabi, 2017).

**Table 3.2:** Variables used in the statistical model

| | |
|---|---|
| $n$ | Number of census tracts in the study area |
| $i$ | Census tract |
| $x_j$ | $j^{th}$ explanatory variables |
| $m_i$ | 2010 Population per census tract |
| $y_i$ | Response variable |
| $\lambda_i$ | Five-year incidence rate. Similar to Seukep et al. (2015) |
| $\beta$ | Estimate parameter |

Here we describe how the model is built based on historical data. Following Seukep et al. (2015), we use the five-year counts for census tract $i$ in the historical data, which is denoted by $y_i$.

Let $n = 1879$ represent the number of census tracts in the study area in the historical data. The variable $m_i$ represents the 2010 population for census tract $i$, in the scale of 10,000 people. The variable $x_{ij}$ is the $j^{th}$ explanatory variable for census tract $i$ where $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, p$ and $p = 5$ for the five environmental explanatory variables. In the spatial Poisson regression analysis, the response variable, $y_i$, is modeled by a Poisson distribution. That is, $y_i \sim Poisson(m_i \lambda_i)$ where $\lambda_i$ is interpreted as the five-year incidence rate. In particular, $\lambda_i$ is modeled by a log-linear model:

$$(1) \qquad \log(\lambda_i) = \beta_0 + \beta_1 x_{i1} + \cdots + \beta_p x_{ip}$$

Based on the estimated statistical model in (1) and the projected explanatory variables at a future year (e.g., year 2020), $x = (x_1, \dots, x_5)$, the predicted annual incidence rate per 10,000 people is obtained as:

$$(2) \qquad \lambda = \frac{\exp(\widehat{\beta}_0 + \widehat{\beta}_1 x_1 + \cdots + \widehat{\beta}_p x_p)}{5}$$

Here the right-hand side of (2) is divided by five because the model in (1) is for the five-year rate and we adjusted the five-year rate to obtain the annual rate. The significant land cover variables in Seukep et al. (2015)

**Table 3.3:** Estimated Regression Coefficients and Significance for Environmental Variables

| | Estimate | Standard Error | Z-Value | Pr(>\|z\|) |
|---|---|---|---|---|
| (Intercept) | 0.16109 | 0.17148 | 0.939 | 0.3475 |
| CWED H-D | 0.00021 | 0.00103 | 0.202 | 0.8397 |
| TECI H-D | -0.01706 | 0.00277 | -6.157 | 7.40e-15*** |
| TECI F-H | 0.0065 | 0.00202 | 3.211 | 0.00132** |
| % Developed | 0.01293 | 0.00164 | 7.880 | 3.28e-15*** |
| % Herbaceous | 0.040396 | 0.00124 | 32.512 | <2e-16*** |
| Significant Codes: 0 (***), 0.001 (**), 0.01 (*) | | | | |

After all datasets were compiled, including CWED for herbaceous-developed edge, TECI for forest-herbaceous and herbaceous-developed edge, percent developed land, and percent herbaceous land, we used the prediction in (2) to determine projected incidence rate of Lyme disease in each census tract, at each decadal time period, and under each of the four IPCC SRES scenarios across the southeastern United States per 10,000 people. The data were then imported into ArcGIS 10.5 and aggregated to census tracts. The data were classified in the figures by a natural breaks classification in which the classification seeks to partition the data in to classes based on natural groups in the distribution of the data. Results from the model gave projected incidence rates, and those rates were classified into land cover suitability categories: None, Low, Medium, and High suitability for Lyme disease transmission. The rates that were then classified into categories are 0 (None), 0 - 0.5 (Low), 0.5 - 1.0, 1.0 - 2.0 (Medium), 2.0 - 4.0, and 4.0 - 10.0 (High) cases per 10,000 people for better geovisualization. Geovisualization is an important process when analyzing and presenting spatial data as it aids in data analysis, synthesis, interpretation, and presentation of the results (Dykes, Maceachren, & Kraak, 2005).

## 3.6 Results

This study identified potential future land cover suitability for Lyme disease distributions in the southeastern United States under four different scenarios. Specifically, we identified census tracts that may have an amplified risk of Lyme disease in the study area based on variables that were previously found to have a significant relationship with Lyme disease incidence in Virginia. Overall, the greatest potential Lyme disease risk occur in the Southeastern Plains and Middle Atlantic Coastal Plain ecoregions of the study area (Figure 3.1). Large cities in the study area such as Atlanta, Georgia, Charlotte, North Carolina, and Richmond, Virginia do not show a heightened risk of Lyme disease perhaps due to the density of developed land and lack of ideal edge environments to support the disease transmission cycle.

As expected, the results vary based on the specific scenario used to quantify Lyme disease incidence for the study area, given the variation in the underlying land cover data. Figure 3.3 shows the temporal pattern of the highest category of potential land cover suitability under each scenario. The A2 scenario shows the greatest increase in land cover suitability for Lyme disease with an average increase of 16,163.95 $km^2$ per decade within the highest category (Table 3.3); the growth rate is exponential, with the area of the highest incidence category increasing more rapidly each decade following 2050. The specific areas of highest potential suitability in the A2 scenario include the Southeastern Plains, northern Piedmont, and Ridge and Valley (Figure 3.4). The area of the highest category of potential land cover suitability under the A1B scenario increases, on average, 3,458.47 $km^2$ per decade (Table 3.3); the scenario increase is nearly linear. The ecoregions where the highest land cover suitability category include the Southeastern Plains and the northern Piedmont (Figure 3.5).

Conversely, the B1 and B2 scenarios showed an average decrease in potential land cover suitability by 2100. The area of highest land cover suitability category under the B1 scenario decreases 595.7 $km^2$ on average per decade (Table 3.3). The decrease is stead over time, leveling off around 2040 and staying consistent throughout the decade thereafter (Figure 3.6). The area of highest land cover suitability category in the B1 scenario include the Southeastern Plains and northern portion of the Ridge and Valley, with a reduction in total area of the highest category by 2100. Finally, the B2 scenario shows the greatest average decrease of the area of potential land cover suitability. The area rapidly decreases beginning in 2020, then levels off around 2060, and has a consistent total area for the highest suitability throughout the rest of the century. With an average decrease of 2,006.83 $km^2$ per decade (Table 3.3), the B2 scenario is the scenario with the greatest decrease of potential land cover suitability for Lyme disease of the four scenarios (Figure 3.7). Areas of highest suitability in this scenario include the Southeastern Plains and the Ridge and Valley ecoregions.

## 3.7 Discussion

The results of this research provide an indication of where the Lyme disease transmission cycle may be supported in the coming decades as the extent of the disease's distribution continues to expand southward, following the trend of the past several decades. The results showed variation depending on the land cover scenario selected, as the varied land cover under each scenario will impact the Lyme disease transmission cycle differently. If future land cover change follows the path of the A2 or A1B scenarios, enhanced Lyme disease may occur in the southeastern United States, while if the B1 or B2 scenarios are followed, we can expect a decrease in areas where the transmission cycle will be supported.

Under the A2 scenario, land cover suitability for Lyme disease is expected to experience the most rapid increase through 2100 of the four scenarios examined here. This scenario is characterized by rapid population growth, which results in high rates of land conversion for developed uses because of an absence of policies to restrict the urban sprawl (Sleeter et al., 2012). Additionally, the high population growth along with a reduced emphasis on environmental conservation results in intensified logging and forest harvesting (Sleeter et al., 2012). Combined, the expected land use changes will result in greater levels of fragmentation and the exponential increase of areas projected to have the highest Lyme disease incidence through 2100.

Under the A1B scenario, land cover suitability for Lyme disease is also expected to increase through 2100. This scenario considers environmental regulation a secondary concern to economic growth, and urbanization increases, which impacts agricultural and forested lands (Sleeter et al., 2012). Due to a rapidly increasing population, increased urbanization, and a lesser focus on environmental regulation, fragmented landscapes increase (Sleeter et al., 2012), resulting in increased edge environments that support the Lyme disease transmission cycle.

A subtle decrease in areas with the highest land cover suitability for Lyme disease is expected under the B1 scenario between 2020 and 2100. This scenario has the same population growth as the A1B scenario with similarly high levels of economic growth, but this scenario, however, considers a high level of environmental and social awareness, along with a global view of sustainability (Sleeter et al., 2012). Urban areas expand slowly due to preferences towards compact development, and significant efforts are made to increase protected forested land. Restoration and protection of natural land covers are common themes in this scenario (Sleeter et al., 2012). These factors combine to result in lower levels of fragmentation and edge environments that in either the A1B or A2 scenarios.

Finally, under the B2 scenario, the area with the highest levels of land cover suitability for Lyme disease experiences the greatest decline of the four scenarios. Due to low population growth and an environmental sustainability characterized by this scenario, urban areas grow the slowest in this scenario compared to the other scenarios (Sleeter et al., 2012). Forested area in this scenario is stable, but demand for biofuels contributes to increased rates of forest disturbance (Sleeter et al., 2012). Due to the societal focus on environmental sustainability, total forested area increases by 2100, resulting in the least amount of fragmentation and edge environments of the four scenarios.

Overall, these results support future land cover change decision-making in the study area as Lyme disease continues to expand southward. Careful landscape design, following the B1 or B2 scenarios, can help prevent the establishment of the Lyme disease transmission cycle by inhibiting host and vector interactions. This finding supports recommendations of Jackson et al. (2006), who researched the role of land cover patterns in endemic areas, specifically, Maryland. Jackson et al. (2006) suggests that designing landscapes against efficient Lyme disease transmission environments, such as with fewer forest-herbaceous edges, will prevent the further distribution of Lyme disease.

While we attempted to manage their influence, several limitations in this study need to be considered. As we sought to focus on ecological contributors to the Lyme disease transmission cycle, this research did not include the statistically significant demographic variables found in Seukep et al. (2015), which were population density, median age, and median household income. Future attempts to project Lyme disease in the future should consider variation in underlying human characteristics, including demographic factors. The census tracts used as the basic unit of analysis were from the 2010 census, and the research does not include changes in the number of census tracts or shape changes in the future, which occur following each decennial census. The spatial resolution of the land cover scenario raster images was relatively coarse, at 250-meter resolution; however, this dataset is the only available projected land cover data, and projecting land cover at a resolution finer than 250m would be challenging. Finally, in order to correctly maintain identities of each census tract, original census tract polygons were transformed to a raster image with the same spatial resolution as the projected land cover scenarios to import into the FRAGSTATS 4.2 software. After edge variables were derived from FRAGSTATS 4.2, the raster census tract layer was converted back into a shapefile using the non-simplified version, meaning the new census tract polygons maintained the gridded shape of the raster image, in order to maintain the correct number and identity of census tracts to join each table to the census tract layer in ArcGIS 10.5. This could result in error since census tracts normally do not have gridded shapes and areas inside the converted census tracts could overlap the true shape of a different census tract.

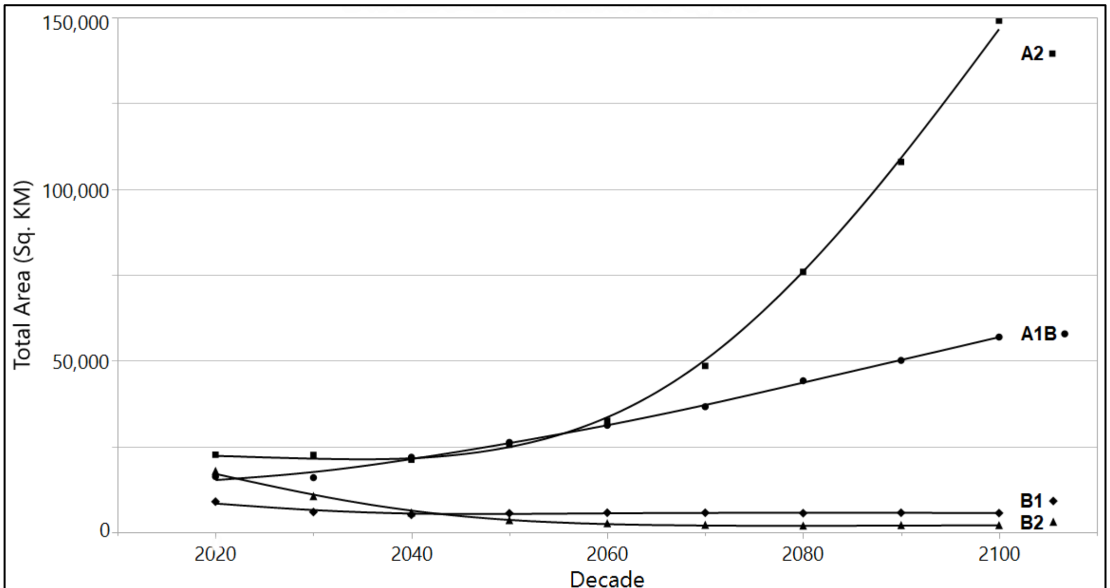
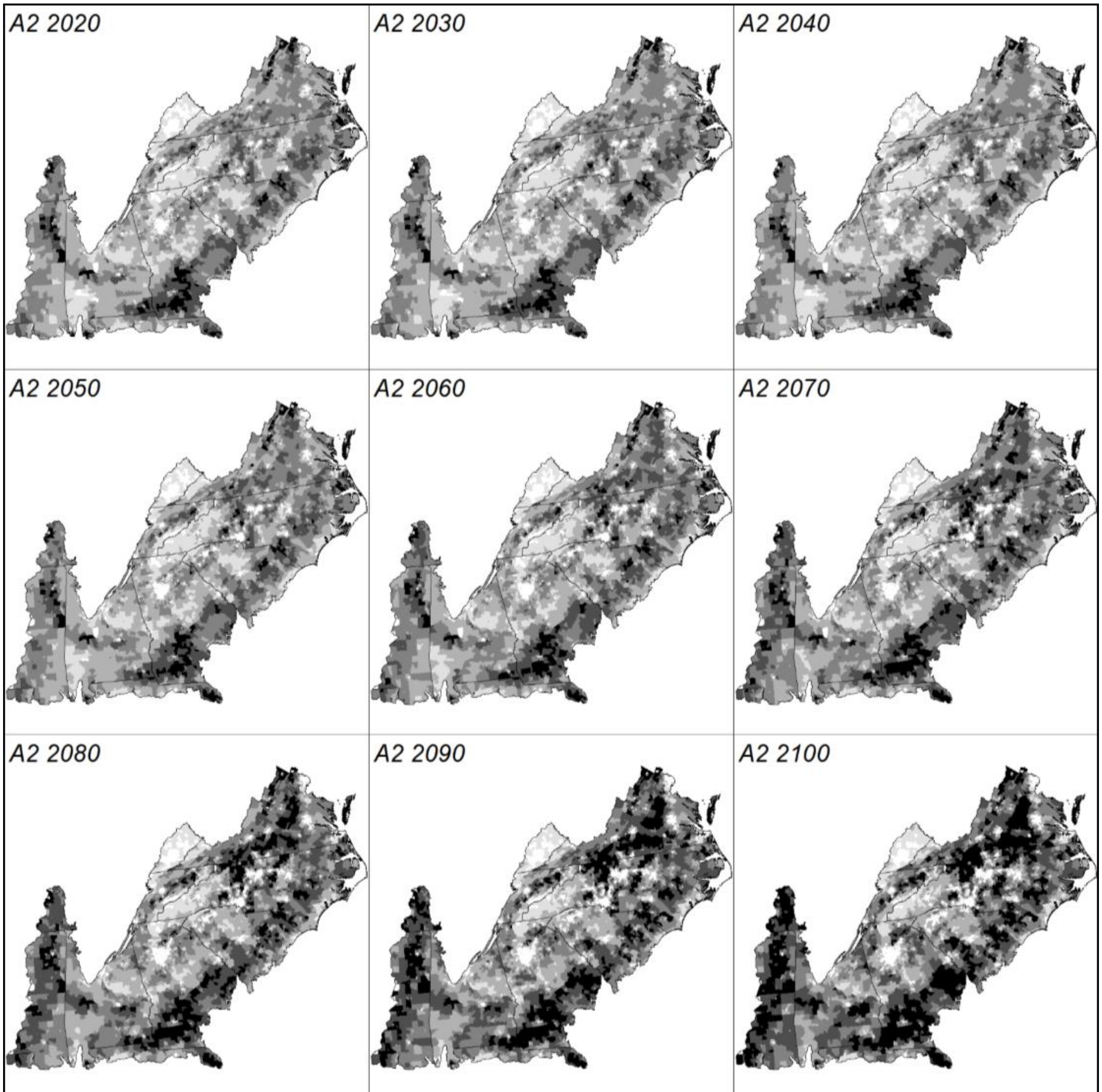



**Figure 3.3:** Total area ($km^2$) of the highest land cover suitability for each decade through 2100 under four IPCC-SRES scenarios



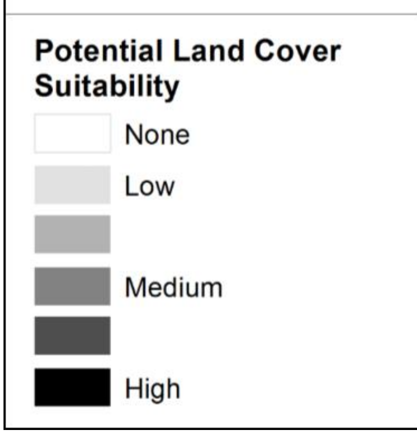
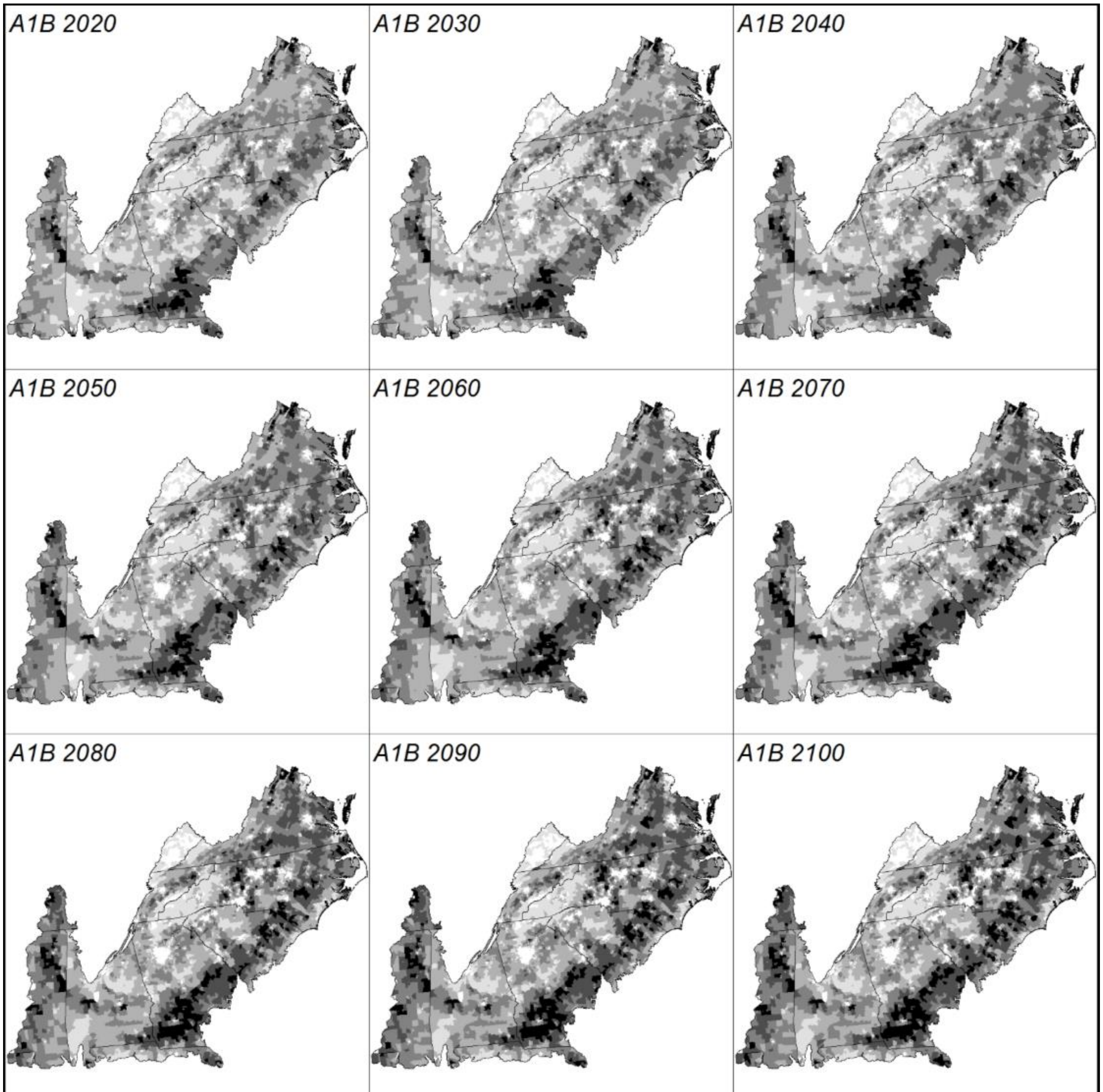




**Figure 3.4:** The A2 scenario is characterized by the consistent increase in population over time and regionally-oriented economic development. This scenario results in the most rapid increase in potential land cover suitability for Lyme disease.



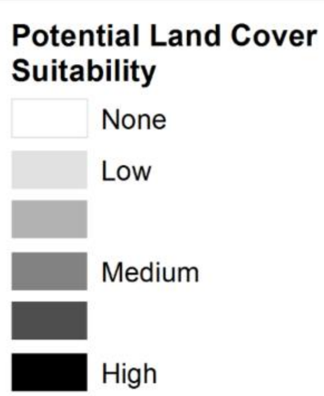
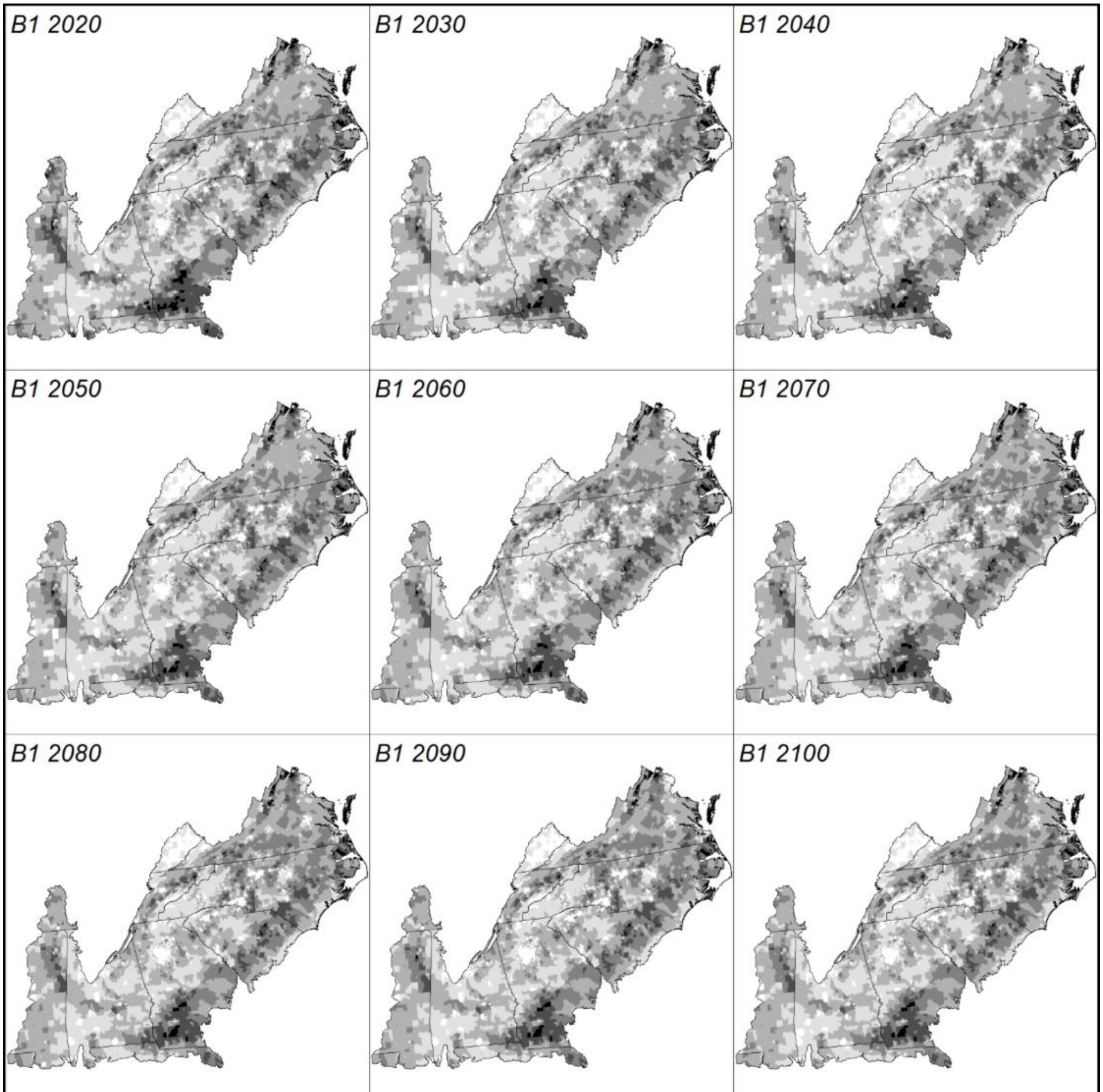




**Figure 3.5:** The A1B scenario is characterized by rapid economic, population, and technological growth. This scenario demonstrates a steady increase of potential land cover suitability for Lyme disease.



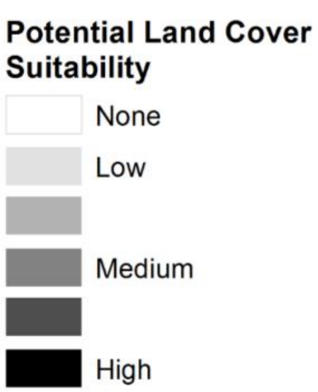




**Figure 3.6:** The B1 scenario is characterized by rapid changes in economic structures toward a service and information economy, with the introduction of clean, resource-efficient technologies (IPCC, 2018). The scenario results in a decrease in potential land cover suitability that level off around year 2040.

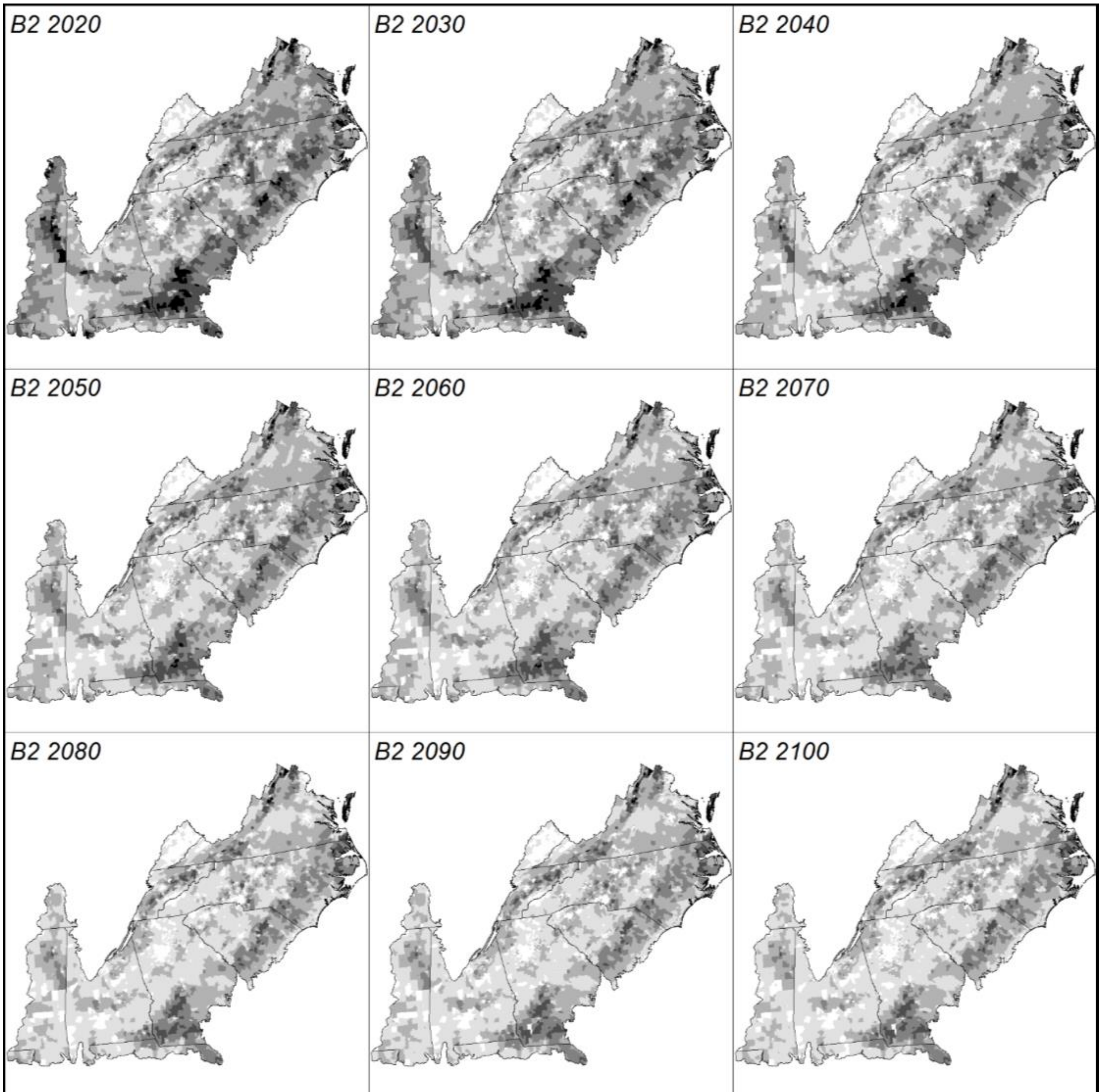



**Figure 3.7:** The B2 scenario represents an emphasis on local solutions to economic, social, and environmental sustainability needs. Global population gradually decreases over time with less rapid and more diverse technological change compared to the A1B and B1 scenarios. This scenario results in the largest decrease in potential land cover suitability, leveling off below the B1 scenario's results around year 2060

**Table 3.3:** Total Area for Highest Land Cover Suitability Category for Each Scenario ($km^2$)

| | ***A1B*** | ***A2*** | ***B1*** | ***B2*** |
|---|---|---|---|---|
| **2020** | 16,254.44 | 22,609.76 | 8,963.13 | 17,843.89 |
| **2030** | 15,949.13 | 22,569.64 | 5,926.26 | 10,507.02 |
| **2040** | 21,902.38 | 21,181.27 | 5,129.50 | 5,751.82 |
| **2050** | 26,218.08 | 25,544.01 | 5,583.58 | 3,546.45 |
| **2060** | 31,192.16 | 32,536.46 | 5,729.89 | 2,589.58 |
| **2070** | 36,615.91 | 48,475.42 | 5,725.82 | 2,140.26 |
| **2080** | 44,184.79 | 75,877.67 | 5,608.80 | 1,920.87 |
| **2090** | 50,113.85 | 107,956.20 | 5,724.50 | 2,052.49 |
| **2100** | 56,916.09 | 149,064.36 | 5,629.76 | 2,052.49 |
| **% Change from 2020 - 2100** | **350.16%** | **659.29%** | **62.81%** | **11.50%** |

## 3.8 Conclusion

Lyme disease is the most significant vector-borne disease in the United States. The current extent of Lyme disease includes the eastern United States, the upper Midwest, and the west coast, however, 95% of all Lyme disease cases in the United States are contracted along the east coast (CDC, 2017). In addition, five counties that were not previously considered endemic have met the clinical surveillance criteria for Lyme disease in North Carolina, representing a continued southward advance (Lantos et al., 2015). Therefore, this study answered the following basic research question, based on current relationships between Lyme disease and land cover characteristics, how will future land cover configurations affect the distribution of Lyme disease throughout the southeastern United States? No previous study has attempted to use land cover variables correlated with Lyme disease in its present endemic area to project areas where the Lyme disease transmission cycle may be supported under different scenarios. This study has identified areas in the southeastern United States potentially at risk of increased Lyme disease as it moves into these areas using projected land cover data developed under four scenarios representing a diverse set of assumptions  for population growth, economic growth, and technological growth over time (IPCC, 2018).

The results of this research demonstrated that, based on the significant environmental variables found in Seukep et al. (2105), it is possible to reduce Lyme disease risk, as argued by Jackson et al. (2006). If we have high energy and resource demands, and delayed development of renewable energy (IPCC, 2018), the conditions will be right for the Lyme disease transmission cycle. However, if we focus on reducing pollution, developing renewable energies, and promote sustainable lifestyles, then the Lyme disease transmission cycle could be reduced in the future based on the land cover variables associated with Lyme disease risk. As humans modify the surrounding environment, the choices made can contribute to or prevent disease emergence, including the continued emergence of Lyme disease.

As Lyme disease continues to emerge in the southeastern United States, this research can aid in education efforts related to Lyme disease prevention. In addition, this research can be used as a tool to city planners in these areas in order to implement efforts to adjust the landscape and potentially reduce Lyme disease transmission. The temporal results of this research can support control and prevention efforts inside the study area as new regions become endemic by considering actual development patterns and the results under the four projected land cover scenarios. The projected land cover scenarios are an important part of this research in that the data represent four different future scenarios that signify four directions that could lie ahead regarding emissions, population growth, economic growth, technological expansion, and environmental sustainability to name a few. Since the data are aggregated to census tract level, a finer scale than county data, officials can pinpoint areas of concern in which planners and developers can consider the amount of developed land and herbaceous land and the levels of edge environments when creating new development projects to limit ideal environments for host-reservoir interaction. The results of this research and current Lyme disease information can aid in the reduction or limitation of forest-herbaceous and herbaceous-developed edges and the structure of those edges in order to constrain Lyme disease transmission.

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