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Shane M. Tripp
Binghamton University--SUNY, stripp1@binghamton.edu

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PRESCRIBED FIRE AND DEER TICKS: A MANAGEMENT METHOD FOR THE PRIMARY VECTOR OF LYME DISEASE IN THE EASTERN UNITED STATES

BY

SHANE M. TRIPP

BA, Binghamton University, 2014

THESIS

Submitted in partial fulfillment of the requirements for
the degree of Master of Arts in Geography
in the Graduate School of
Binghamton University
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2017

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in the Graduate School of
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Mark A. Blumler, Chair and Faculty Advisor
Department of Geography, Binghamton University

Naomi W. Lazarus, Member
Department of Geography, Binghamton University

Qiusheng Wu, Member
Department of Geography, Binghamton University

Ralph M. Garruto, Member
Department of Anthropology, Binghamton University

ABSTRACT

The United States is currently amid a public health crisis caused by the bacteria, *Borrelia burgdorferi*, that is responsible for Lyme disease.   A deer tick, *Ixodes scapularis*, is the primary vector for these bacteria in the Eastern United States and its explosive population increase and range expansion in the past several decades is responsible for the rapid spread of the disease. Understanding the cause of this growth is dependent on the habitat characteristics that determine the deer tick's abilities to survive, reproduce, and disperse into new areas and the changes that may have released it from historic limits. Fire suppression policy and its adverse ecological effects may be the primary cause and implementation of prescribed fire management may be the best solution for reducing tick densities, changing habitat characteristics to less suitable conditions, and stopping or reversing the tick's geographic range expansion. This pilot study sampled from natural areas under prescribed fire management in Central Pennsylvania and found that populations of ticks may remain significantly lower several years after burning. Effects of the size of burns and the clustering of burn areas, as well as the relative importance of burning compared to other environmental characteristics is yet unclear. Many changes should be implemented in future iterations of this study to uncover patterns that may yet exist. This knowledge may be key to management of the Lyme crisis.

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I would like to express my deepest gratitude to my advisor, Dr. Mark Blumler, for providing the theoretical inspiration for this research and for the constant guidance, advice, and expertise that was invaluable in making it the best it could be. Additionally, I would like to thank my committee members: Dr. Ralph Garruto, Dr. Naomi Lazarus, and Dr. Qiusheng Wu, for your consultations and incisive feedback throughout this process. This thesis would not be half as good without all your input. I am also grateful to all the excellent faculty and staff from the Geography and Biology Departments that have taught me so much over these several years. I am further indebted to the Pennsylvania Game Commission, the Albany Pine Bush Preserve, and the many other land managers, preserve directors, and ecologists I communicated with throughout the planning of this research. Nobody, however, has been more important to me in the pursuit of my goals than my family, friends, and partner. The unwavering interest and encouragement of my parents and brother helped me push ahead whenever times were tough. My friends were there for me every time I needed a break or to have some fun. And my partner, Liza Knipscher, not only has been an incredible source of encouragement and inspiration but also provided an incalculable amount of feedback and advice for many of the early drafts of this thesis. These words do not even begin to express how much I truly appreciate everything that you all have done to help me get to where I am today.

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INTRODUCTION

Nature is always in a state of flux. Countless interrelated systems have constant cascading effects on each other. The frequency and intensity of these changes have increased dramatically since humans have come to dominate the world. A common reaction to this has been to think that change altogether is always bad but these changes can have positive results (Botkin 1990). It is the responsibility of scientists and leaders to understand this and work toward a functional and diverse natural world that can include humanity indefinitely.

One issue that is in dire need of better understanding is the expanding geographic range of *Borrelia burgdorferi*, the bacterium that causes Lyme disease in North America. The species primarily responsible for transmitting a disease between other species is termed the vector species. *Ixodes scapularis*, commonly called the blacklegged or deer tick, is the primary vector for Lyme disease in the eastern United States. The tick has been slowly spreading from two high density foci of historic endemicity, or native areas, throughout the Northeast and Great Lakes regions (Humphrey, Caporale, and Brisson 2010). The situation has become a public health crisis as Lyme disease risk threatens human and non-human communities wherever the tick becomes established.

This is largely of an issue of human-environmental interaction. Strong arguments can be made that human alterations of the landscape over the past few centuries have led directly to this issue. It is also clear that major actions must be taken if this issue is to be controlled or reversed. The natural environment must be the main focus for attempts to understand this issue. The deer tick, its hosts, and other involved species all live in and depend on the ecological functioning of their habitats. These species all react to changes in habitat characteristics that may further lead to cascading effects throughout the ecosystem. Effective environmental management must be formulated with an understanding of these changes.

The movement of deer ticks as they disperse and expand their established range is a biogeographic phenomenon. The range of habitable environments that these ticks successfully live and reproduce within is growing. Scientists must strive to understand the species' methods of dispersal and the factors controlling their successful establishment and population increase. Fire is key to formulating this understanding.

Fire suppression was a zero-tolerance policy for wildfires in the United States. It dominated environmental management throughout the 20th century coincident with forest regrowth after the widespread abandonment of agricultural lands in the Northeast. The consequences of this fire exclusion may include the enablement of deer ticks to spread as they are doing today. Prior research has largely suffered from inconclusive results but some studies have suggested that reintroduction of fire into these ecosystems may help to reverse these trends.

Prescribed fire is the intentional setting of fires in the environment for several purposes. Humans have been using fire as an environmental management tool for millennia but it has only come into favor with parts of the scientific community in recent decades. Prescribed burning is an extremely new practice in scientific environmental management of the Northeastern United States and its potential relationship with deer tick ecology is not very well understood. However, it may be the key to successful Lyme disease management.

This paper is meant to serve as a pilot study for establishing an understanding of the relationship between fire, deer ticks, and other ecological and geographic features of the Northeast. Can fires of a size and frequency typical of prescribed fire management alter environmental conditions enough to maintain reduced tick populations long after the ecosystem has recovered? Understanding these relationships is vital to successful management of this issue. Blumler argues that fire suppression is the primary cause of this crisis (2003). Further, Gleim et al. suggest that long-term annual prescribed fire management may be key to nullifying Lyme disease risk in infested areas and to stopping the tick’s spread into uninfested areas (2014). Morlando, Schmidt, and LoGiudice propose that use of prescribed fire may be critical to managing Lyme disease indefinitely (2012). Success in these goals would have tremendous significance for human and environmental health in the future. This paper will investigate the potential of prescribed fire management as a control method for the population growth and range expansion of the deer tick in forests of the Northeast.

LITERATURE REVIEW: FORESTS, FIRE, AND BIOGEOGRAPHY

Biogeography of Lyme Disease and the Deer Tick

The Lyme Disease Crisis

Lyme disease is the common name for the disease Lyme borreliosis and is caused by *Borrelia burgdorferi* bacteria. It is vectored by ticks but has also been found within (but not transmitted by) fleas, mosquitoes, and other biting flies (Biesiada et al. 2010). Hard-bodied ticks of the *Ixodes* genus are the major vector group. *I. ricinus* is Europe's tick vector while *I. pacificus* is in the Western United States and *I. scapularis* ranges throughout the Eastern United States (Biesiada et al. 2010; Wormser et al. 2006). Different regional strains, or genotypes, of Lyme disease coincide with different tick species and with regional genotypes of each tick species (Wormser et al. 2006).

The disease is of critical importance because its symptoms are severely debilitating if victims are not treated shortly after infection. It is recommended that protective clothing and repellants are used if venturing into tick habitat and full-body checks are carried out at the end of each day (Wormser et al. 2006). Immediate post-bite treatment with antibiotics is highly effective because infection takes at least twenty-four hours (Biesiada et al. 2010). Once infected, the bacteria spread throughout the body and attack multiple organ systems including the bones, muscles, nervous system, and heart. Different Lyme strains exhibit some symptom variation but there is usually a progression of stages with increasing severity if untreated (Wormser et al. 2006). Typical early symptoms include skin lesions and sporadic muscle or joint pain. Later symptoms can include severe neurological pain and abnormalities, heart disease, and internal organ lesions. Successful late-term treatment can still leave victims with chronic life-long symptoms that are not well understood and need further research (Biesiada et al. 2010).

Deer Tick Life History

Ixodes scapularis is an ectoparasitic arachnid with a two-year life cycle and three distinct life stages. The middle stage, called nymphs, and the adults can transmit the bacteria that cause Lyme. Two other dangerous but less common diseases are also known to be vectored by this tick. Human granulocytic anaplasmosis is caused by *Anaplasma phagocytophilium* and is a bacterial infection that targets white blood cells. Human babesiosis is caused by the protozoan parasite, *Babesia microti*, that attacks red blood cells (Wormser et al. 2006). Trans-ovarial transmission of these diseases from the mother to its eggs is extremely rare and the first stage, called larvae, are virtually never infected (Guerra et al. 2002). Approximately eighty percent of tick larvae die before becoming nymphs while mortality rates of later stages remain high but improve markedly with each successive stage (Wilson 1998).

Nymphs are the most likely disease vector for humans because of their near-microscopic size, higher abundance compared to adults, and the early summer timing of their quests coinciding with when humans are most frequently in forested areas (Ostfeld et al. 2006). Questing is the search for a vertebrate host from which to take a blood meal and is the period of highest vulnerability for the deer tick. Adults quest from fall to spring whenever the ambient air temperature is above their tolerance threshold of approximately 4°C (41°F) and larvae quest in late summer (Duffy and Campbell 1994). The optimal temperature for questing is 25°C (77°F) and activity decreases sharply above or below this level (Vail and Smith 2002). Deer ticks quest on forest floor vegetation and in leaf litter where relative humidity stays high enough to avoid desiccation even on hot, dry days (Schulze, Jordan, and Hung 2001). Questing activity above the forest floor is common but decreases drastically when relative humidity is even just marginally below one-hundred percent and mortality rates are high when microclimatic relative humidity dips below seventy-five percent (Vail and Smith 2002). Hosts range in size from small rodents to large ungulates depending on the life stage of the tick. Most other time is spent hidden in leaf litter molting, overwintering, and looking for mates (Ostfeld et al. 2006). These behavioral patterns determine changes in their geographic distributions over time.

Tick Distribution Before European Colonization

Much biogeographical study has focused on the northward migration of many species following the climate change and glacial retreat at the end of the last ice age. Understanding these types of patterns is essential to managing movement of the same organisms resultant of contemporary environmental changes (Humphrey, Caporale, and Brisson 2010). Genetic investigations can be compared to gathered knowledge of a species' evolution and biogeography to draw conclusions key to understanding these patterns (Humphrey, Caporale, and Brisson 2010).

Long-distance deer tick migrations are believed to be due to migratory bird hosts carrying infected ticks or slower migration on land through low density corridors between better suited regions. Such occurrences are believed to have led to the establishment of the deer tick population centers in the Northeast and the Upper Midwest from the South. Researchers used genetic analysis to pinpoint the order and timing of migrations to shed light on how these organisms reacted to changing climatic and human patterns in the past and predict future migrations (Humphrey, Caporale, and Brisson 2010).

Rates of gene flow in ticks within and between regions confirm that northeastern and midwestern populations share a much closer common ancestor than either does to southeastern populations. Phylogeographic patterns also show that northeastern populations are descended from a small number of migrants from southeastern populations after the last glacial retreat (Humphrey, Caporale, and Brisson 2010). Midwestern ticks' genetic patterns indicate more recent population establishment. It fits with what would be expected of a migration event having occurred within several hundred generations followed by a more recent population explosion (Humphrey, Caporale, and Brisson 2010). Northeastern ticks' genetic patterns also show rapid rates of evolution characteristic of a recent population explosion. This pattern is absent in the southeastern populations where the species has likely maintained low densities since glacial periods (Humphrey, Caporale, and Brisson 2010).

Habitat Suitability

Environmental characteristics that determine whether an area can sustain a reproductive population of deer ticks depend on the scale of analysis. A broad-scale study sampled closed canopy deciduous forests from all the continental United States east of 100°W. This includes all the known distribution of the deer tick and the Lyme bacterium in eastern America (Diuk-Wasser et al. 2006). A spatial model was constructed that included tick counts, climate, vegetation index, altitude, forest fragmentation, and soil type. Analysis confirmed that the species is expanding its range. Two major and one minor center of dispersal conformed to expected density relationships of surrounding areas and beyond (Diuk-Wasser et al. 2006). These foci are the Long Island and Upper Midwestern endemic populations as well as a smaller coastal New England population. These regions exhibit the highest recorded densities with surrounding densities decreasing at rates consistent with expected species range expansion patterns (Diuk-Wasser et al. 2006). High humidity and seasonal temperature variation were determined to have a strong positive relationship with deer tick presence on a national scale. High densities of tick populations were most strongly correlated with the presence of established populations in adjacent areas (Diuk-Wasser et al. 2010).

Vegetative cover in forests is an ecological trait that has serious implications for the conditions of the forest floor. These conditions are major determinants of microhabitat suitability and actual distributions of deer ticks (Schulze and Jordan 2005). Even differences on minute spatial scales within seemingly uniform areas may have a strong influence on where deer ticks can survive. Variation within leaf litter and shrub layers alter microclimates in subtle but important ways (Schulze and Jordan 2005). Dense shrubs stabilize temperature and increase humidity while also potentially reducing predation on ticks and their host species (Prusinski et al. 2006).

Soil conditions have notable influence over deer tick habitat suitability as well. Too dry of soils can lead to desiccation and death but excessive soil moisture negatively affects ticks overwintering in leaf litter and the upper horizons of soil. This may be because of soil moisture’s facilitation of predation and parasitization of ticks by soil organisms (Guerra et al. 2002). Thus, coarse soils are more likely to harbor high deer tick densities than clays, and sandy barrens habitats may be highly vulnerable to invasion compared to other habitat types (Guerra et al. 2002).

General patterns show that deciduous forests usually harbor higher tick densities than coniferous forests and that maple forests usually harbor higher densities than oak forests (Guerra et al. 2002; Ostfeld et al. 1995). Researchers sampled heterogeneous mixed hardwood and pitch pine forests around a naval installation in New Jersey and found that deer tick populations were positively correlated with ecotonal areas, habitat fragmentation, hardwood tree dominance, shrub density, and leaf litter depth (Schulze and Jordan 2005). This species was found in much lower numbers in pine dominated areas. A relationship was inferred between pine forests' comparatively high temperatures and low humidity and the survival and reproduction of the deer tick. Dense shrub covers can moderate this effect in these areas (Schulze and Jordan 2005). Researchers concluded that spatial variation over as little as a few meters has a large effect on microhabitat suitability. Annual variations of climatic and environmental characteristics on all spatial scales create a state of constantly shifting microhabitat conditions that determine the yearly distribution of deer ticks within infested areas (Schulze and Jordan 2005).

Host presence and abundance are of noted importance for deer tick establishment but not without some uncertainties. The presence of suitable hosts for all life stages is needed for survival and reproduction but tick densities may not decline significantly as host densities are reduced (Levi et al. 2016). High proportions of nymphs and adults can concentrate on fewer host individuals in conditions of low host availability with only marginal increases in tick mortality rates. Larval mortality rates are high under any conditions and any change due to lowered host abundance is statistically insignificant

(Levi et al. 2016). Many areas well within dispersal range have sufficient host species populations but remain uninfested (Wilson 1998).

Lyme and Deer Tick Dispersal

Borrelia burgdorferi are spirochete-type bacteria that are vectored by ticks and carried by their vertebrate hosts (Blumler 2003). Each host species acts as a reservoir for the bacteria and have different levels of competency, or the capability to carry and pass on the disease when fed upon (Humphrey, Caporale, and Brisson 2010). Highly competent species in the Northeast include important tick hosts such as deer mice and white-tailed deer (Ostfeld 1995).

The Lyme bacterium is reliant on continual transmission between its hosts and vectors to reproduce and spread because neither host nor vector are known to pass it on to their offspring (Humphrey, Caporale, and Brisson 2010). Lyme is thus tied to the evolutionary and biogeographic history of its vector organisms. It thrives in the presence of competent reservoir species and an abundance of ticks (Humphrey, Caporale, and Brisson 2010). Likewise, it cannot easily spread or grow to high densities in the absence of these factors.

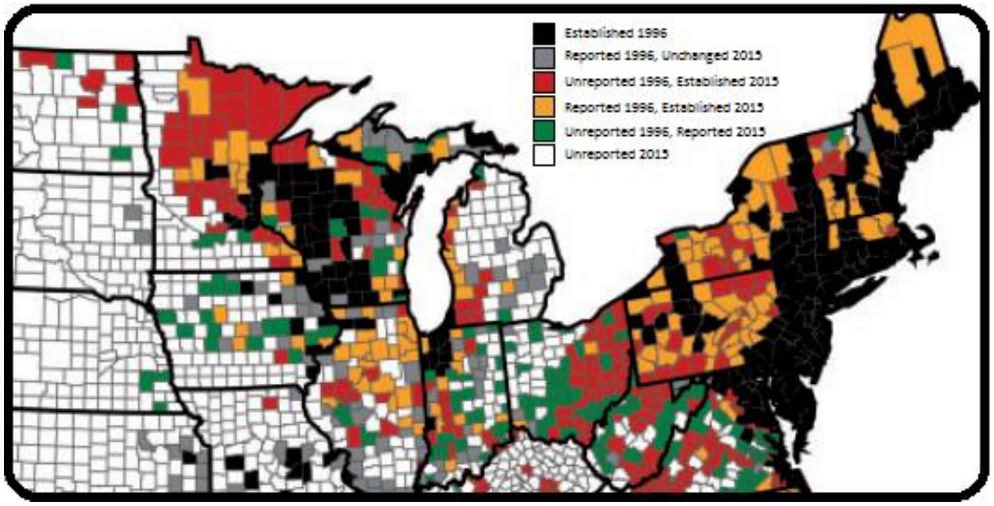


Figure 1 – Northeastern United States Deer Tick Range Expansion Map, Modified Inset from Eisen, Eisen, and Beard (2016)

Per the NYS Department of Health, the tick was only present in 22 of the 62 counties in New York State in 1989. That number grew to 60 in just ten years (Prusinski et al. 2006). A survey of county officials and local acarologists found that the tick may now be found in parts of every county of New York and is established in significantly more counties of the Northeast and Midwest than just twenty years ago (Eisen, Eisen, and Beard 2016; Figure 1). This is remarkable because individual ticks crawl only a few meters during their quests for hosts. Thus, their collective dispersal distance is dependent on the natural ranges of their three hosts during their two-year life cycle (Madhav et al. 2004).

This distance and the effective dispersal rate of the species can be modelled based on the hosts available and each host species' movement tendencies. Simulations found that deer were the only host with major significance in range expansion rates (Madhav et al. 2004). White-tailed deer are the main hosts for adults and have large habitat ranges. This is what makes them the main dispersers of deer ticks and Lyme, especially along riparian corridors (Guerra et al. 2002). High abundance of mice greatly increases local Lyme prevalence but may slow tick dispersal by diverting a large proportion of immature ticks from larger ranged hosts (Guerra et al. 2002; Madhav et al. 2004). Medium-sized mammals may negatively influence tick dispersal because of high host preferability for adult ticks and smaller individual home ranges compared to deer (Madhav et al. 2004). The importance of birds in tick dispersal varies per each species' host potential and migration patterns. Species with seasonal migrations coinciding with the questing periods of immature ticks have high potential for long distance dispersal (Guerra et al. 2002). The American robin, for example, has contributed greatly to deer tick and Lyme disease dispersal while most other bird species have had lesser importance (Madhav et al. 2004). Temporal variation in each of these species movements in relation to deer tick activity patterns throughout a year plays a large part in the expanding spatial distribution of tick populations (Ostfeld et al. 1995).

Interaction between patches in a landscape also plays an important role in the success or failure of dispersal through that landscape. Patch connectivity is the characteristic that measures the movements of organisms and non-living materials through a landscape. Similar patch types generally have higher connectivity and an organism's status in a landscape may depend on the geographic distribution of patches with high ecological suitability (Pickett, Wu, and Cadenasso 1999). Patch characteristics such as size and shape may also play a role in these population processes (Ostfeld et al. 1995).

Pests usually do well in landscapes with broadly homogeneous patch structures (Pickett, Wu, and Cadenasso 1999). Frequent disturbances can disrupt this homogeneity, however, and keep unstable populations within desirable bounds (Wu and Loucks 1995). Populations can persist by frequent recolonizations from undisturbed areas but local extinctions within patches can coincide with significant decreases in the total number of suitable patches in a landscape and increases of the distances between them to decimate metapopulations (Wu and Loucks 1995; Pickett, Wu, and Cadenasso 1999). Humans are effective at creating disturbance that alters the spatial and temporal dynamics between and within patches (Ostfeld et al. 1995). This ability may be effective for decreasing dispersal of pests such as the deer tick through a landscape.

Patches each have different levels of habitat suitability per species as discussed above. These characteristics influence the rates of immigration, successful colonization probabilities, and eventual population stability of deer ticks. New introductions may be frequent but successful establishment is unlikely per each individual. Each occurrence largely depends on the habitat characteristics in the immediate vicinity of female adult ticks after detachment from their final hosts (Wilson 1998). This specific location is key to dispersal success because of the small dispersal range of larvae and their hosts. Larvae are unlikely to survive long if born in unsuitable detachment sites. Thus, ticks usually can only successfully disperse into or through areas when there are stable source populations nearby and enough suitable habitat at the detachment point for a complete life cycle. Establishment of new stable populations usually requires repeated successful introductions and numerous large patches of high quality habitat (Wilson 1998).

Ecological Hypotheses

Lyme disease is unique among modern public health crises in that it is primarily rooted in ecological occurrences. This has had the effect of focusing much of the research on the purely ecological factors influencing its hosts and vectors while geographic perspectives have been generally overlooked (Blumler 2003). There are multiple hypotheses attempting to explain the Lyme disease epidemic that each largely ignore geography. The rapidly increasing deer densities throughout the East in recent decades is one popular explanation for explosive deer tick expansion but it cannot wholly account for this phenomenon. Coastal California is concurrently experiencing a similar Lyme epidemic with *I. pacificus* but deer populations were never decimated as they were in the 1800’s throughout the East (Blumler 2003).

Other touted hypotheses involve changes in trophic interactions favoring tick host populations by way of increased acorn production and changes in predator species compositions (Blumler 2003). The relationship between ticks, Lyme disease, and these trophic interactions is poorly understood but disruption of this relationship can lead to drastic consequences. Dramatic change in populations of organisms in one trophic level usually has cascading effects on species at every trophic level throughout an ecosystem (Levi et al. 2012).

One study examined data collected from a study site in southeastern New York over a 13-year period. Variables included deer ticks, temperature, precipitation, white-tailed deer, chipmunks, mice, and acorn masts (Ostfeld et al. 2006). Most of the variables were found to range from mostly to totally insignificant. The strongest positive correlation was found between tick nymph density, rodent populations one year prior, and acorn masts two years prior (Ostfeld et al. 2006). This suggests that fluctuations of rodents and their food resources are valuable predictors of Lyme disease risk. The many ecosystems that are not oak-dominated, however, may exhibit different patterns.

The near-total eradication of grey wolves has had far-reaching effects on the ecological and biogeographic nature of nearly the entire continent (Levi et al. 2012). One such effect may be that trophic shifts in the northeastern United States now favor the Lyme bacterium and its hosts and vectors. Around 80-90% of ticks infected with Lyme in the Northeast contracted the disease from just a few species of small rodents including white-footed mice and eastern chipmunks (Levi et al. 2012). These small rodents have a strong trophic relationship with small and mid-size predators such as the red fox whose populations are influenced by the behavior of other predators.

Foxes have a particularly strong proclivity to not only preferentially hunt small rodents but to stockpile killed prey when their populations are undergoing explosive growth such as during oak mast years (Levi et al. 2012). This is a regular control on rodent populations and acts as a counter to the increased pathogen risk associated with rodent population oversaturation. Additionally, foxes intermix well with human environments that border forests and other natural areas with the highest risk of Lyme disease (Levi et al. 2012).

Coyotes have become the dominant large predator in the northeast since the eradication of grey wolves. They compete directly with foxes and other smaller predators despite having hybridized with remnant wolf populations and thus favoring larger prey such as deer (Levi et al. 2012). Consequently, coyotes put significantly less trophic pressure on small rodent populations than red foxes.

Fox numbers and distributions have been shrinking since the establishment of coyote dominance in the region. Rodent populations are now less suppressed by higher trophic levels which leaves periods of explosive growth comparatively unchecked (Levi et al. 2012). Lowered predation also slows the rodent populations' generational turnover rates. Long-lived generations increase the chance of infection spreading further and faster because infected individuals will transmit the bacteria to more ticks in their lifetime (Levi et al. 2012).

These trophic phenomena are undoubtedly factors for the northeastern deer tick dispersal foci but cannot be a primary cause. California is far removed from these regional shifts despite its concurrent Lyme disease explosion. It is likely that these ticks and the bacterium will yet reach much higher populations and expand to much wider geographic distributions. Many more habitats exist that are ecologically viable for deer tick establishment but have not yet been colonized (Blumler 2003). Analysis of every major ecological, historical, and geographic variable as well as of organismal population growth and dispersal patterns over time leaves the policy of fire suppression as the only factor that is shared between the two main eastern foci and coastal California. The nationwide historical and geographic patterns of the use of controlled burns as an environmental management tool perfectly align with the patterns of deer tick growth and spread (Blumler 2003).

Historical records show that this practice was used in virtually all regions of the United States to some degree by both Native peoples and European settlers until the policy of fire suppression took hold in the early twentieth century (Blumler 2003). This policy's widespread implementation except in southeastern regions, where rural people defiantly continued burning the forests, aligns well with the bacterium's current spatial distribution (Blumler 2003).

History and Science of Burning

Forest Regrowth in the Absence of Fire

Environmental management plans often aim to restore areas to pre-European settlement conditions. This is problematic because relatively little is known about these conditions and the available records are likely biased toward descriptions of areas favorable to human travel and settlement. This issue is compounded by the fact that so little is known about the range of natural variation that occurs in ecosystems on time scales much larger than humans can truly comprehend (Tiedemann, Klemmedson, and Bull 2000).

Research conducted on this topic shows that very few stable plant assemblages have ever existed. Nature is dynamic and different species adapt to change in radically different ways (Tiedemann, Klemmedson, and Bull 2000). Long-term forest change is directly related to the ecophysiological factors of the species within them. The role each species fills changes through space and time dependent on these factors (Abrams and Nowacki 2016).

There was a large degree of variation between regions and habitat types but fires were especially prominent in oak-dominated ecosystems prior to fire suppression policy (Greenberg, Otis, and Waldrop 2006). Investigations have shown that these ecosystems were far more widespread in eastern deciduous forests during the past 10,000 years until the 20th century (Shumway, Abrams, and Ruffner 2001).

Oak trees have low shade tolerance compared to most competitors so some regularly occurring disturbance is likely necessary to facilitate their dominance over other large tree species. Most oak species are comparatively resilient to fire effects so frequent fire is the most widely accepted explanation for oak dominance. Proposed ignition sources range from lightning strikes to indigenous peoples and European-Americans intentionally and unintentionally starting fires (Shumway, Abrams, and Ruffner 2001).

This relationship between fire and eastern forest composition has been demonstrated at various temporal scales. Observational studies of post-fire competitive regeneration have shown dramatically increased oak numbers compared to the pre-fire communities. Fire scar studies on very old trees have suggested fire intervals between two and twenty-four years in many eastern forests over the past several centuries. Finally, paleoecological investigations have found high oak pollen levels in the past 1500 years highly coincident with charcoal, suggesting a strong relationship between oaks and fire (Shumway, Abrams, and Ruffner 2001).

Clearcutting and regrowth under fire suppression policy changed the nature of these and other forests. Densities of mid-level and understory vegetation are much higher. Vegetative dynamics shifted to give a competitive edge to species that were only minor elements of these ecosystems for countless centuries prior (Greenberg, Otis, and Waldrop 2006). Oak-pine forests are now far less numerous while fire-intolerant maple species underwent a massive increase (Abrams and Nowacki 2016). Fire suppression may also be tied to increases of problematic organisms and associated diseases such as the chestnut blight and Dutch elm disease (Blumler 2003).

Some pollen records show vegetative composition changes were greater in the last 150 years than in the prior 850 years (Abrams and Nowacki 2016). Baseline ecological functioning underwent dramatic and irreversible shifts in many cases. Twentieth century management methods are clearly untenable but returning to pre-settlement conditions may not be possible or even desirable (Ryan, Knapp, and Varner 2013). Future management will likely need to re-incorporate fire and other types of disturbance into ecological regimes to best accommodate both humans and the rest of nature.

The Science of Burning the Woods

Fire suppression almost immediately dominated federal forest policy after the establishment of national forests in 1891. Studies used to justify these policies throughout the early 1900’s virtually always concluded in their favor (Stephens and Ruth 2005). Stakeholders in the southeastern United States argued in favor of burning, however, and prescribed burns were eventually sanctioned on federal land in Florida during the 1940's. Shortly thereafter, studies documenting increased fuel loads and fire risk resultant from decades of fire suppression in the West and Southeast were accepted by leading scientists and policymakers (Stephens and Ruth 2005). Tides were beginning to shift away from fire suppression and, in 1963, a federally requested study titled the Leopold Report officially connected this policy to its adverse environmental effects. Prescribed fires then became slowly more common until fire was officially embraced as essential to most ecosystems by the 1995 fire policy revisions (Stephens and Ruth 2005).

Scientific consensus and government policy have come to favor fire as a prime ecosystem management strategy in recent decades. Prescribed fire and surrogate strategies that emulate its effects are now touted as essential to maintaining the health of ecosystems country-wide (Greenberg, Otis, and Waldrop 2006). However, its effects on the incredibly complex systems and individual elements present in the natural environment are severely under-studied. What is not ambiguous is that many of these areas are in unhealthy or dysfunctional states and need comprehensive and well thought out management plans that may include the use of prescribed fire (Ryan, Knapp, and Varner 2013).

The primary objective of burning is usually to alter the vegetative characteristics of the environment without reducing the quality or quantity of the desirable characteristics (Wilkinson 1979). Burning affects all aspects of an ecosystem, however, and the way that it affects these characteristics also varies between ecosystems. Just a few of these characteristics include "nutrient pools, integrity and function of the forest floor, plant species composition, soils, wildlife, water yield and quality, air quality… [and] long-term forest productivity," (Tiedemann, Klemmedson, and Bull 2000, 2).

Areas fully restored with mechanical treatment and prescribed fire often exhibit changes such as high tree mortality, increased snags, decreased understory density, a more open canopy, and strongly reduced leaf litter (Greenberg, Otis, and Waldrop 2006). Immediate effects may cascade to affect baseline ecological functioning as well. For example, fire may shift forest compositions from maple to oak dominance. This would lead to changes in characteristics of the leaf litter layer, soil moisture dynamics, and microclimates under the canopy (Arthur et al. 2012).

Intense fires can decimate forest floor nutrient levels through oxidation and volatization. Prescribed fire timing should ideally be planned to occur when the top layer of the forest floor is dry enough to burn but lower layers are too moist (Tiedemann, Klemmedson, and Bull 2000). This helps maximize the benefit of fire while minimizing its destructive ability. Habitat elements of disproportionate importance to vulnerable species should be preserved. These could include standing dead trees called snags. Several mammals and birds make nests in snag cavities while countless invertebrate species living within the decaying wood are vital food sources for other organisms. Features like this can be isolated from the effects of fire with firebreaks so that the area can benefit from the burning without losing its most vital components (Tiedemann, Klemmedson, and Bull 2000).

These results are essential for maintaining the health of most mature, fire-tolerant forest ecosystems. Occurrence of fire clearly has many benefits but it is an inherently destructive force. It is important to understand how it will affect each characteristic on a case-by-case basis before adoption of this practice into an environmental management plan. Societal pressures may also preclude options that might be best for ecological purposes. Nearby human communities, for example, may restrict fires to low intensities or even restrict management to inferior surrogate strategies such as mechanical or chemical thinning (Arthur et al. 2012).

Ticks and Prescribed Fire

Tick Control

The modern use of prescribed burning in environmental management is advancing faster than our understanding of its various effects. This is especially true regarding fire's effect on ticks and their hosts (Allan 2009). Any organism that spends part of its life cycle on the ground or in low vegetation is vulnerable to properly timed burns, including ticks (Blumler 2003). Fire is known to reduce tick numbers initially by killing them directly and by the destruction of their leaf litter habitat. Post-burn recolonization rates of ticks and their hosts are far less understood. The dominant biotic and abiotic factors that control these rates likely vary between species, habitat type, and climate (Allan 2009).

Determination of the complete distribution of deer ticks followed by conduction of controlled burns in strategic locations may be key to halting its further dispersal (Blumler 2003). Action to control this expansion is most effective when timed for early summer to coincide with nymphal deer tick questing for hosts (Diuk-Wasser et al. 2006). Additionally, burning would likely reduce populations of deer ticks and its associated organisms in areas that are already infested (Blumler 2003).

The threat of epizootic diseases such as Lyme is greatest when its hosts and vectors are numerous (Blumler 2003). White-footed and deer mice fill a major niche in Eastern forests as predators, prey, and seed dispersers. They are also major larval and nymphal deer tick hosts and are highly competent reservoirs for the bacterium that causes Lyme disease. A study area in mountainous oak-dominated forests in Western North Carolina was used to test the hypothesis that forest mice do well post-fire (Greenberg, Otis, and Waldrop 2006). Untreated control plots exhibited an average of 7% growth in mouse populations from the timing of pre-treatment to post-fire, burnt areas grew by 53%, and areas that underwent full restoration averaged 82% growth. The increased habitat heterogeneity, or spatial diversity of habitat characteristics, of the restored areas likely favors forest mice due to increased food sources and refuge from predators (Greenberg, Otis, and Waldrop 2006). Buskirk and Ostfeld demonstrated that deer tick density limits may be sensitive to variations in larval and nymphal host availability (1995). Thus, this relationship between rodents and fire may be an important counter-effect that needs to be accounted for when burning for tick control.

Early Examinations of Prescribed Fire's Effects on Ticks

Results of studies conducted on this topic in the past have largely been vague and inconclusive. However, the methods of these studies have nearly all involved conditions unlike real-world prescribed fire management. Site selection of areas that were only burnt once experimentally, that are small in geographic size, or of areas previously unburnt for decades are inappropriate for gauging the effectiveness of prescribed burning for tick management. Real prescribed fire practices usually include areas from hundreds to thousands of acres repeatedly burnt at varying intervals (Gleim et al. 2014). These are the conditions under which the relationships between ticks and fire should be examined because there are long-term environmental changes that result from real-world management that these studies fail to consider. Studies must also account for spatial and temporal variation in host abundance, microclimate, and vegetation structure as these are known to affect tick populations as much as any human actions (Gleim et al. 2014). Tick abundance is a useful indicator that these characteristics are suitable for their survival and reproduction but it has some limitations. All life stages must be present in an area to be able to confirm establishment although low numbers could either be a sign that conditions are unfavorable or just that colonization is still in its early stages (Guerra et al. 2002).

One study investigated the relationship between larvae populations of the lonestar tick species and deer abundance in oak-hickory ecosystems of the Missouri Ozarks under long-term burn management. Researchers chose twelve burn units ranging from 61 to 242ha under a general plan of low-intensity spring burns every 3-5 years and cloth-drag surveyed for questing ticks (Allan 2009). Statistical analysis of the data found an initially strong positive correlation of time since the last burn on the number of larvae collected. Lonestar ticks were depleted at first but underwent rapid population growth two years post-burn then crashed back down to pre-burn levels after five years (Allan 2009). The researchers attribute this pattern to high host abundance post-burn. Recolonization rates of many host species are rapid once vegetation grows back. This is likely due to increased foraging ability in areas that are freshly burnt. Infrequent burning regimes may thus exacerbate the problem. These conclusions may be countered by more frequent, longer term, and larger scale burning throughout the encompassing area (Allan 2009).

A classic study of Floridian pine-palmetto woods examined deer ticks in burn patches of at least one square mile in size. These researchers determined that it took more than three years for tick densities to reach pre-burn levels in this habitat (Rogers

1955). Early contemporary research on deer ticks and prescribed fire examined patterns in two four-hectare mixed hardwood forest plots in Connecticut. Areas were sampled immediately post-burn and in the following fall. An immediate 100% reduction occurred that was later nullified by identical samples in experimental and control plots taken in the fall (Stafford, Ward, and Magnarelli 1998). This study formed a useful basis of research but was far too limited in scale and complexity to draw useful conclusions.

The deer tick was among the tick species most carefully analyzed in a later study of the Southeast. Population levels correlated strongly with burning, season, tree density, and precipitation amount. Long-term burning reduced deer ticks by ~78% (Gleim et al. 2014). Yearly climate differences are likely a major cause for population variation of most tick species. Large area burns slow tick and host repopulation while repeated burning may deplete tick source populations for increased long-term effectiveness (Gleim et al. 2014).

Researchers investigated the relationship between deer ticks and burn-focused environmental management in the Albany Pine Bush Preserve in New York during the 2007 growing season. This ecosystem is inland pitch pine-scrub oak barrens that is reliant on regularly occurring fire to maintain its unique heterogeneous structure and biological composition (Morlando, Schmidt, and LoGiudice 2012). Its wildlife is dependent on fire to maintain specific soil, vegetative, and microclimatic conditions as well as to keep out invasive species. Unfortunately, these areas have been greatly reduced and fragmented since European colonization. What does remain has suffered significant degradation in large part due to the fire suppression policy of the twentieth century (Morlando, Schmidt, and LoGiudice 2012).

Deer ticks are in high abundance throughout the preserve. Preserve employees and volunteers have been carrying out restoration efforts that include removal of invasive black locust trees and returning conditions to the drier and more open historic conditions that are unfavorable to ticks. Restoration strategies include mechanical removal of invasive plants, planting of native species, precise herbicide applications, and prescribed fire (Morlando, Schmidt, and LoGiudice 2012).

Researchers sampled tick densities in three treated and three untreated areas each with ten 100-square meter quadrats. Sampling was timed to coincide with peak densities of all tick life stages (Morlando, Schmidt, and LoGiudice 2012). Densities were measured in each area at these three times in one year. Restored areas were shown to harbor just 2% of the population of nymphal ticks compared to untreated areas. These researchers concluded that full restoration reduces disease risk to near zero (Morlando, Schmidt, and LoGiudice 2012).

CONCEPTUALIZATION OF FACTORS GOVERNING DEER TICK DENSITIES

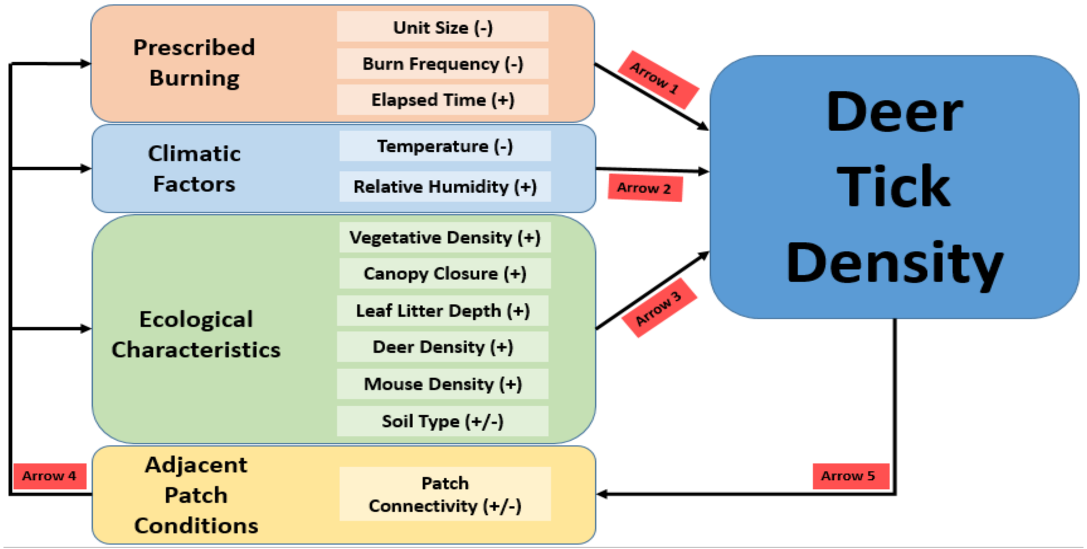


Figure 2 – Deer Tick Density Model

Conceptual Model

Ecosystems are complex and interrelated so a change in one characteristic often has rippling effects throughout the system. Deer tick density in each patch of forest is thus influenced by many different environmental characteristics. Climatic and ecological factors have relatively well understood influence on tick survival, reproduction, and migration. Prescribed burning is a tool for management of these forests that affects tick density in ways that are not fully understood. Additionally, areas nearby the patch under investigation can exert strong influence onto said patch.

Temperature and humidity are the baseline determinants of deer tick density. Temperate climates with temperatures above freezing for most of the year are necessary for their reproductive rates to exceed mortality rates but lower microhabitat temperatures during the growing season are favorable to their survival and reproduction (Duffy and Campbell 1994). Increased relative humidity decreases desiccation risk while questing and increases survival and reproductive rates (Vail and Smith 2002; Figure 2: Arrow 2). If the climate is too hot and dry, then deer ticks likely will not survive for long and cannot establish a stable population in that area.

Rodents and white-tailed deer are the most important host species for deer tick survival and reproduction. Rodents are the preferred hosts for larvae and nymphs and are also the Lyme reservoirs that are most important for the spread of the disease (Ostfeld et al. 2006). High rodent density is usually a positive influence on deer tick density (Figure 2: Arrow 3). White-tailed deer are the primary hosts for adult ticks and thus their presence is usually necessary for establishment of a stable population in an area and increased deer densities likely lead to increased tick densities (Ostfeld et al. 2006; Figure 2: Arrow 3).

Soil type and canopy closure both have indirect effects on the establishment and growth of deer tick populations. Soil type can increase tick density if they hold enough moisture to maintain high humidity levels but have enough drainage that they do not become easily inundated. Tick density is usually lower in wetlands (Guerra et al. 2002; Figure 2: Arrow 3). Canopy closure affects microclimate by regulation of temperature and maintenance of high humidity on the forest floor (Arthur et al. 2012). Open canopies can expose these areas enough that they become too hot and dry in summer for ticks to survive in high numbers. Higher canopy closure likely leads to increased tick densities (Figure 2: Arrow 3).

Leaf litter depth and forest floor vegetative density may be the most important ecological factors determinant of deer tick density. Leaf litter is the primary habitat of the deer tick. Larvae and nymphs spend almost the entirety of their existence in leaf litter other than the few days they are feeding on their hosts. Adults likewise typically live in leaf litter when they are not questing or feeding. The absence of a leaf litter layer as primary habitat may completely preclude deer tick establishment in an area (Schulze, Jordan, and Hung 2001). Habitat suitability may then increase slightly as litter depth increases above zero (Figure 2: Arrow 3). High forest floor vegetative density is important habitat for questing adult ticks and can greatly boost the density of all life stages. Dense thickets of ferns, shrubs, grasses, and other shorter plants regulate temperature and humidity on the forest floor. They also provide protection from predators for ticks and key rodent host species (Prusinski et al. 2006). Tick densities likely increase as vegetative density increases (Figure 2: Arrow 3).

Prescribed burning interacts directly or indirectly with every other variable in these forest patches. Fires cause direct ecological shifts that alter microclimatic conditions throughout the burnt area. Fire’s effects on host species are among the most ambiguous. In most cases, deer can escape the fire and then return for the high-quality regrowth forage. Mice and other rodents in areas burnt are directly killed and depleted because most rodent burrows offer no protection from moderate intensity burns. However, forage quality is very high for mice after a fire and populations can rapidly recover (Greenberg, Otis, and Waldrop 2006). Factors controlling the balance between direct kills and post fire migration are not well understood. Canopy closure, leaf litter depth, and forest floor vegetative density are all reduced by prescribed burning. Reduced vegetation increases the porosity of soils (Greenberg, Otis, and Waldrop 2006). These all have the effect of reducing the microhabitat and climatic suitability of these areas for deer ticks. Finally, burning directly affects ticks. Direct kills typically reduce densities to near zero immediately following the burn (Blumler 2003). Burn units are known to be recolonized some time afterward but factors governing the rate and level of recolonization are not fully understood. Burn unit areal size and time since burn are the key variables for predicting tick density after a prescribed fire (Gleim et al. 2014). Larger burn units may slow recolonization for increasingly long-term reductions (Figure 2: Arrow 1). Time since the last burn compared to tick density will help determine this. More frequent burning within a larger area may also increase tick reduction longevity (Figure 2: Arrow1).

Burn patches are not independent of the environment surrounding them. The level of connectivity between patches is variable but the climatic, ecological, and burn history characteristics of any given patch affect adjacent patches (Pickett, Wu, and Cadenasso 1999; Figure 2: Arrow 4). The importance of this interaction for deer tick densities is not fully understood but high tick densities in an adjacent patch may lead to more rapid recolonization of a recently burned patch (Figure 2: Arrow 5). These observations lead to testable hypotheses regarding these interactions.

Hypotheses

Prescribed fire can result in long-lasting deer tick reductions when burns are large in area and conducted regularly.

Null Hypothesis 1 (Ho1): Deer tick reductions from prescribed burning do not persist longer than two years from when the burn was conducted.

Alternative Hypothesis 1 (Ha1): Deer tick reductions from prescribed burning persist longer than two years.

Null Hypothesis 2 (Ho2): There is no relationship between deer tick density and the size of the area burned.

Alternative Hypothesis 2 (Ha2): Prescribed burning creates longer lasting reductions in deer tick density as the size of the area burned is increased.

Null Hypothesis 3 (Ho3): Repeated burning throughout an area does not alter the duration of resultant deer tick reductions.

Alternative Hypothesis 3 (Ha3): Repeated burning throughout an area creates longer lasting deer tick reductions.

Null Hypothesis 4 (Ho4): Ecological or climatic factors are the primary determinants of deer tick densities in areas undergoing prescribed fire management and fire characteristics are secondary.

Alternative Hypothesis 4 (Ha4): Fire characteristics are the primary determinants of deer tick density in areas undergoing prescribed fire management and ecological and climatic factors are secondary.

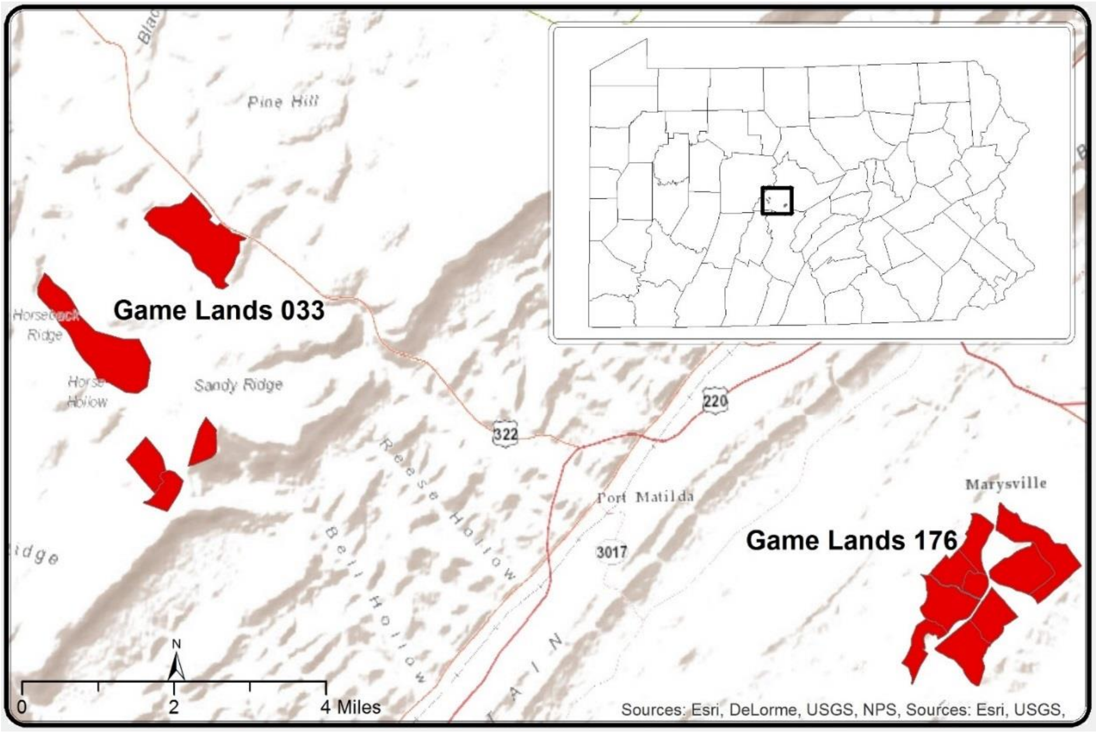
STUDY AREA

Central Pennsylvania Scotia Barrens

The study areas where these hypotheses will be tested are within the Pennsylvania Game Lands 176 and 033 that are managed by the Pennsylvania Game Commission (Figure 3). Specific land units for study are of the oak barrens and pine barrens ecosystem types that are dependent on regular occurrence of fire to maintain their ecological integrity. Game Land 176 is oak-dominated while Game Land 033 is pine-dominated. The Game Commission has conducted annual prescribed burns in different patches throughout these lands since 2010 (Pennsylvania Game Commission 2016).

These spatially heterogeneous ecosystems are dominated by pitch pine trees and various large oak species in the overstory while birch, maple and cherry trees are not uncommon cohabitants. Various saplings and shrubs such as scrub oaks form sometimes dense thickets in the understory while ferns and other herbaceous plants are thick in some areas of the forest floor. Barrens are especially common on ridges with sandy, well-drained soils although Game Land 176 is of average elevation. Regular burning maintains open canopies, lower vegetative densities, thinner leaf litter layers, and high habitat heterogeneity. Humidity is relatively low while temperatures tend to experience greater variation. Species diversity is high and many threatened, endangered, and rare species depend on the healthy functioning of these areas for their survival. Lack of fire can lead to dominance by fire intolerant species, increased vegetative densities, and a general reversal of many important characteristics of these ecosystems (Pennsylvania Game Commission 2016).

Selection of study areas of closely related ecosystem types is important to isolate geographic and temporal variation while minimizing the effects of ecological variation between areas on tick densities. Ecological characteristics determinant of tick densities should only vary between patches according with expected successional shifts over time since the last prescribed burn. Ecological characteristics should thus correlate well with time since burn so that this variable and areal size of burns can be better analyzed in relation to observed tick densities.



Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS,

Figure 3 – Study Area Map

Specific burn patches in these game lands vary in geographic size, time since last burn, and in proximity to each other and to unburnt areas. Eight burn units in Game Lands 176 are centered around a small road and sit within the northeastern part of the larger area. They vary in size between 59 to 203 acres and different patches have been burnt yearly since 2010. Four burn units in Game Lands 033 are accessible by a dirt road and are spread throughout the larger area. They range between 90 and 517 acres in size and were burnt from 2014 to 2016. These burn units are all within ten miles of each other.

METHODOLOGY

Data Acquisition

Burn characteristic data was acquired directly from GIS files supplied by the Pennsylvania Game Commission. Geographic location was derived in addition to the size of each burn unit in acres and the time of the last burn per unit. Time is portrayed in years since the last prescribed burn in that area. Field data was collected directly by visiting these areas and taking samples from every burnt unit and two unburnt control units during peak nymph and adult densities in June and October of 2016, respectively.

The primary dependent variable of tick density is collected by a drag cloth method. A drag cloth is a simple but elegant tool made from a square meter cut of white corduroy. A wood pole is sewn into one end with a rope attached for a handle. A chain is sewn into the opposite end to give the apparatus more weight. The drag cloth is pulled along the forest floor of a sampling area and deer ticks instinctively latch onto it. Nymphs and larvae tend to be under-sampled by this technique in dense vegetation because they tend to quest near the ground but relative densities will be adequate for comparison if done carefully (Ostfeld et al. 1995).

Three 100-square meter plots were randomly placed in each burn unit and in unburnt control areas to be fully sampled. The drag cloth was pulled over the entirety of the plots and checked for ticks every 10-20 meters. Removed ticks were placed in 70% ethyl alcohol for later counting and categorization by life stage.

Climatic and ecological data were recorded in each sampling plot as well. Temperature and humidity at the forest floor was recorded with an electronic thermometer/hygrometer. Canopy cover and understory vegetation densities were visually estimated into percentages. A soil corer was used to measure leaf litter depth in centimeters and to take a soil sample for a visual approximation of soil type. Rodent and deer density sampling are not feasible within the fiscal and temporal constraints of this pilot study and unfortunately are absent from the data.

Data Analysis

The collected data is compiled into tables of each data type per sample plot per burn unit and descriptive statistics per season were calculated (see Appendix). The data was imported into ArcMap GIS software and joined to burn unit shapefiles for examination of spatial patterns. Quantitative statistical analysis with Microsoft Excel and ‘R’ programming software was performed on the data to test each hypothesis for summer and fall data. Descriptive statistics were calculated for categories created for hypotheses 1 through 3 then ANOVA’s were used to compare means between categories. ANOVA’s were used in place of t-tests when comparing two groups for purposes of uniformity with other comparisons and because the results are the same. Regression models were constructed for hypothesis 4.

Means and standard deviation were calculated for each data type for unburnt units, recent burns, and units burnt more than two years ago per each season. Correlation between tick densities and time elapsed since burn was calculated and examined for both seasons. ANOVA tests were then used to compare mean tick densities of all time classes.

More ANOVA tests then compared just the means of unburnt units to units burnt more than two years ago. These test the hypothesis (Ha1) that tick density reductions from prescribed burning can last longer than two years from when the burn was conducted. The tick densities of freshly burnt units were expected to increase from near zero over time but still be significantly lower than in the unburnt patches even after several years.

Means and standard deviation were calculated for each data type for burn areas of greater and lesser than 200 acres per each season. This is approximately the mean size of all burn units in this study. Correlation between tick densities and unit area was then calculated and examined. ANOVA tests were used to compare mean tick densities in burn areas of each size class. ANOVA tests were also used to compare the means of only units burnt more than two years prior in these two size classes. This may help isolate the effect burn unit size has on tick recolonization rates. This tests the hypothesis (Ha2) that tick density reduction longevity increases with increased areal size per burn unit. Larger burn patches should have significantly lower tick densities than smaller patches.

Means and standard deviation were calculated of each data type for burnt units clustered together and units that are not clustered with other burnt units per each season. Clustering in this study refers to sharing more than one edge with another burnt unit and signifies repeated burning in an area. Patches are deemed unclustered if they are isolated within unburnt areas or share only one edge with another burnt unit. ANOVA tests were used to compare mean tick densities of clustered to unclustered units. This tests the hypothesis (Ha3) that tick density reduction is increased under higher frequency prescribed fire management. High connectivity between clustered burnt patches should slow deer tick recolonization enough that densities will be significantly lower than in unclustered patches.

Multiple regression analysis was used to construct models of key determinant factors governing tick densities in these study areas for both seasons. All the variables were scaled using seasonal minima and maxima to between zero and one and initially included in the models. Models of tick densities were constructed with all the numeric variables and then their effects, statistical significance, and collinearity were evaluated. Each model's statistical significance and the amount of variation it explains, or R-squared, were also calculated. Adjusted R-squared is used to account for artificial inflation of R-squared resultant of the inclusion of multiple variables in a model. One model per season uses the three categorical time classes and the other excludes unburnt unit data but uses time elapsed since the last burn instead of classes. Evaluation of these models tests the hypothesis (Ha4) that burn characteristics outweigh ecological and climatic factors when determining deer tick densities in areas under prescribed fire management. The models should predict burn times and burn areal sizes to be statistically significant and have the expected effects on tick densities. Other variables should be less significant, have lesser effects on tick densities than burning, and be heavily correlated with each other.

Table 1 – Summary of Methodology

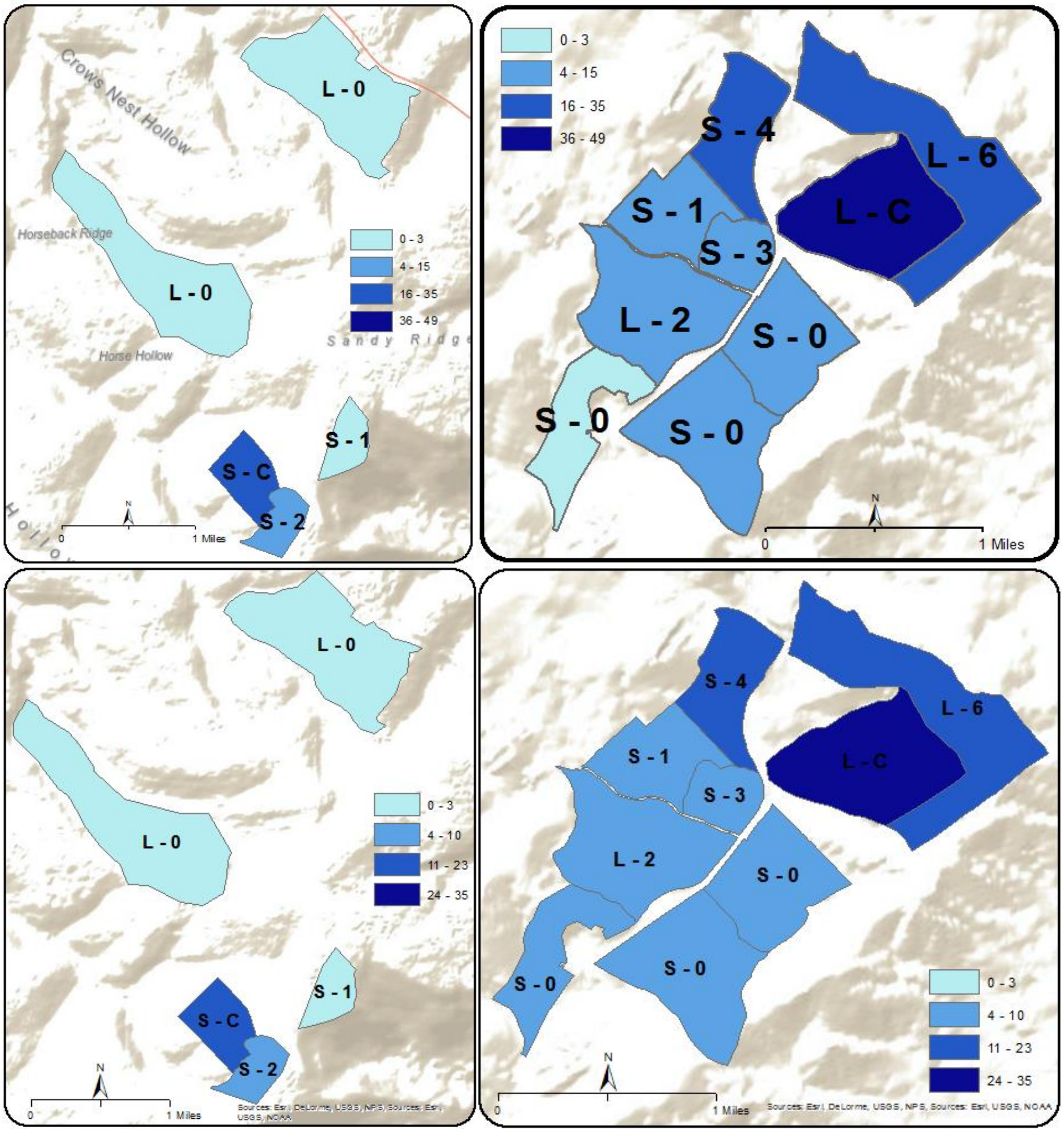
Hypothesis	**Data Acquisition and Preparation**		**Data Portrayal and Analysis**	
	Source	**Structure**	**Method of Portrayal**	**Method of Analysis**
Ho1 **Tick Reductions Last Less No Longer Than Two Years Post-Burn**	Field Collection & GIS Files	Interval/ Categorical	Tables, Map & Descriptive Statistics	Correlation & ANOVA
Ho2 **Tick Density is Independent of Burn Area Size**	Field Collection & GIS Files	Interval/ Categorical	Tables, Map & Descriptive Statistics	Correlation & ANOVA
Ho3 **Frequency of Burning is Independent of Tick Reduction Longevity**	Field Collection & GIS Files	Interval/ Categorical	Tables, Map & Descriptive Statistics	Correlation & ANOVA
Ho4 **Ecological/Climate Factors Outweigh Fire for Tick Density**	Field Collection & GIS Files	Interval/ Categorical	Tables	Multiple Regression

RESULTS

The total area sampled from in each season was 8240 acres and cumulatively 316 ticks were collected from 42 sample plots. Mean tick densities were low with 4 and 3 in summer and fall respectively. Tick densities varied greatly with coefficients of variation of 125 and 133, and samples as large as 19 were collected. Mean canopy cover and understory density each remained just above 40% from summer to fall but mean leaf litter depth unsurprisingly doubled from 2 to 4 centimeters. Overall variation was considerable for these ecological characteristics. Coefficients of variation for canopy cover, understory density, and leaf litter depth ranged from 50 to 100 for both seasons. Every soil sample collected was approximated to be a sandy loam topped with a thin organic layer. Mean temperature decreased from 25 to 20 degrees Celsius between summer and fall with low variation coefficients of 16 and 10. Mean relative humidity only increased from 45 to 48% between seasons and had somewhat higher variation with coefficients of 20 and 18.8 (see Appendix).

Spatial Patterns

Mapping the data reveals a clear pattern of units burnt less than four years prior to sampling having notably fewer ticks than unburnt units and units burnt four or more years prior that is distinguishable at both sample sites in both seasons. It is also notable that unburnt units have higher population densities than units burnt four or more years prior (Figures 4-7).



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Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

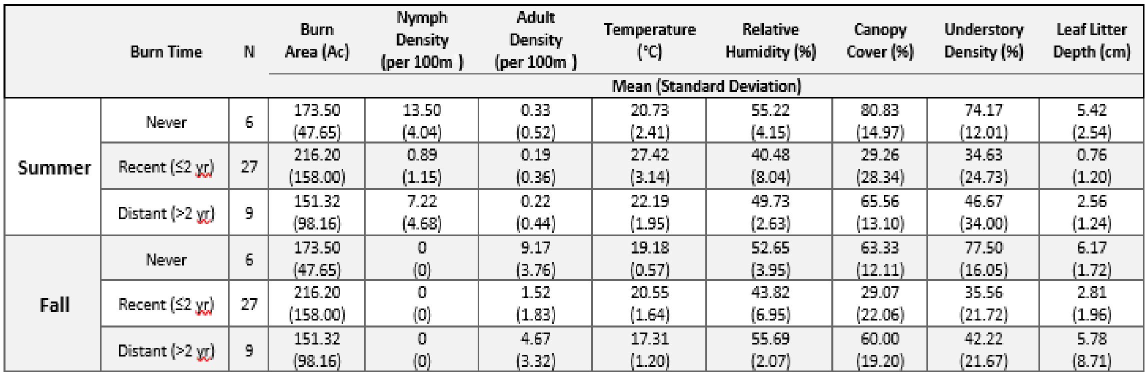
Figures 4-7 – Tick Density Maps of Game Lands 033 & 176.
033 is on left, 176 is on right, Summer is on top, Fall is on bottom.
Densities are the sums of each units' three sample plots. Labels are 'L' for Large (>200 ac) and 'S' for Small (<200 ac) then the number of years elapsed since the last burn or 'C' for the unburnt control units.

There is no clear pattern between unit size and tick densities, however. This may be because there are too few burn units to distinguish subtle differences or that the influence of time since burn masks the size effect. Burn units in the southwestern half of Game Lands 176 are considered clustered in this study and all other units are unclustered. It is possible that the clustering of burns may play a role in those units' comparatively small population densities. Tick densities between seasons follow nearly identical patterns other than the apparent increase in the southwestern-most unit of 176. This could be due to high survivorship between seasons in that unit or just sampling error (Figures 4-7).

Hypothesis 1

Evaluation of the hypothesis that deer tick reductions from prescribed burning do not persist longer than two years from when the burn was conducted requires the examination of the data broken down into time classes per season. Although sample sizes are especially low for unburnt units and units burnt over two years ago (at six and nine, respectively), virtually all data adheres to clear patterns. There are generally high tick densities before burning, severely reduced tick densities immediately post-burn, and mid-range values in units burnt over two years ago (Figure 8-9). Relative humidity, canopy cover, understory density, and leaf litter depth drastically decrease then increase to a lesser degree in nearly every case. Temperature responds similarly but opposite (Table 2).

Table 2 – Descriptive Statistics Per Season and Time Elapsed Since Burn



	Burn Time	N	Burn Area (Ac)	Nymph Density (per 100m)	Adult Density (per 100m)	Temperature (°C)	Relative Humidity (%)	Canopy Cover (%)	Understory Density (%)	Leaf Litter Depth (cm)
			Mean (Standard Deviation)							
Summer	Never	6	173.50 (47.65)	13.50 (4.04)	0.33 (0.52)	20.73 (2.41)	55.22 (4.15)	80.83 (14.97)	74.17 (12.01)	5.42 (2.54)
	Recent (≤2 yr)	27	216.20 (158.00)	0.89 (1.15)	0.19 (0.36)	27.42 (3.14)	40.48 (8.04)	29.26 (28.34)	34.63 (24.73)	0.76 (1.20)
	Distant (>2 yr)	9	151.32 (98.16)	7.22 (4.68)	0.22 (0.44)	22.19 (1.95)	49.73 (2.63)	65.56 (13.10)	46.67 (34.00)	2.56 (1.24)
Fall	Never	6	173.50 (47.65)	0 (0)	9.17 (3.76)	19.18 (0.57)	52.65 (3.95)	63.33 (12.11)	77.50 (16.05)	6.17 (1.72)
	Recent (≤2 yr)	27	216.20 (158.00)	0 (0)	1.52 (1.83)	20.55 (1.64)	43.82 (6.95)	29.07 (22.06)	35.56 (21.72)	2.81 (1.96)
	Distant (>2 yr)	9	151.32 (98.16)	0 (0)	4.67 (3.32)	17.31 (1.20)	55.69 (2.07)	60.00 (19.20)	42.22 (21.67)	5.78 (8.71)

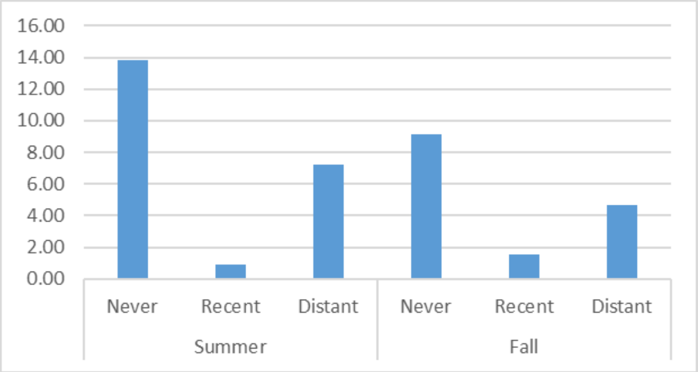


Figure 8 – Chart of Mean Tick Densities Per Season and Time Elapsed Since Burn

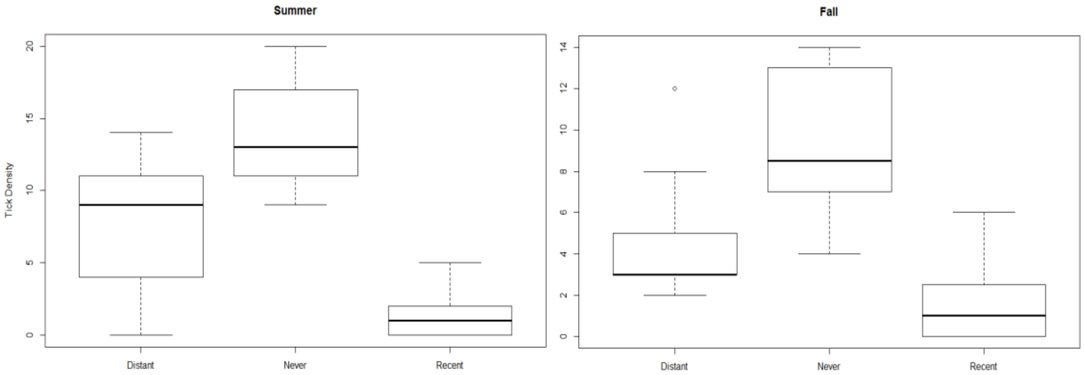


Figure 9 – Boxplots of Tick Densities Per Season and Time Elapsed Since Burn

Table 3 – Correlation per Season between Tick Densities and Time Elapsed Since Burn

	R	df	P-Value
Summer	0.850053	34	*<0.00001*
Fall	0.5608	34	*<0.00001*

Statistically significant ($p<0.00001$) positive correlations exist between tick density and years elapsed since the last prescribed fire in both seasons. A much stronger correlation exists in summer with an r-value of 0.85 while fall is weaker with an r-value of just 0.56 (Table 3). ANOVA tests show statistically significant differences ($p<0.00001$) in the tick density means between all the time classes for both seasons. Nearly 75% of the total variance between time classes is accounted for in summer. This size effect is also high ($\eta^2=0.557$) for fall (Tables 4 & 5). ANOVA tests comparing mean only of samples from unburnt units and units burnt over two years prior also return statistically significant results ($p=0.0202$, 0.0296) for both seasons. The size effects are still high ($\eta^2=0.350$, 0.459) in this comparison (Tables 6 & 7). Total sample size for these tests is only fifteen so these results may only be broadly suggestive of the actual relationship.

Table 4 –ANOVA Test of Summer Tick Densities of All Elapsed-Time Classes

	df	**Sum of Squares**	**Mean Square**	**F-Value**	**P-Value**	**Eta Squared**
Time Classes	2	921.6	460.8	56.16	*<0.00001*	0.742
Error	39	320	8.2			
Total	41	1241.6				

Table 5 –ANOVA Test of Fall Tick Densities of All Elapsed-Time Classes

	df	**Sum of Squares**	**Mean Square**	**F-Value**	**P-Value**	**Eta Squared**
Time Classes	2	309	154.5	24.54	*<0.00001*	0.557
Error	39	245.6	6.3			
Total	41	554.6				

Table 6 –ANOVA Test of Summer Tick Densities in *>2 Years* and *Unburnt* Time Classes

	df	**Sum of Squares**	**Mean Square**	**F-Value**	**P-Value**	**Eta Squared**
Time Classes	1	146.9	146.9	6.996	*0.0202*	0.350
Error	13	273.1	21			
Total	14	420				

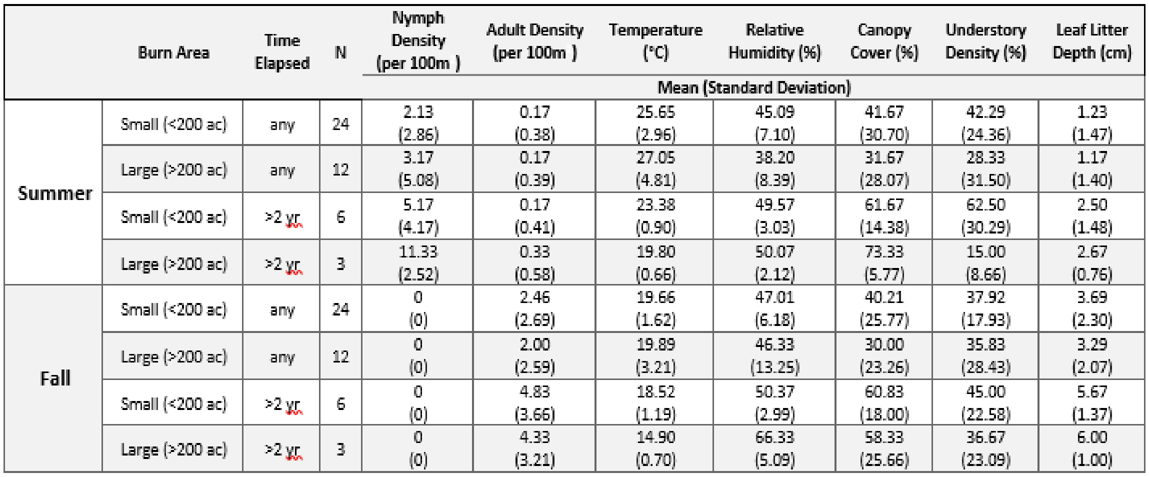
Table 7 –ANOVA Test of Fall Tick Densities in *>2 Years* and *Unburnt* Time Classes

	df	Sum of Squares	Mean Square	F-Value	P-Value	Eta Squared
Time Classes	1	72.9	72.9	5.967	*0.0296*	0.459
Error	13	158.8	12.22			
Total	14	231.7				

Hypothesis 2

Evaluation of the hypothesis that prescribed burning creates longer lasting reductions in deer tick density as the size of the area burned is increased requires the examination of the data broken down into size classes per season, especially of units burnt longer than two years prior. Unfortunately, sample sizes are small and patterns are either indiscernible or entirely absent in the data (Table 8). Worse, sample sizes are only six for the small class and three for the large when excluding samples from units burnt two or fewer years ago. This likely makes size comparisons in this time class of little use and the doubling of summer tick density between small and large units burnt over two years ago can likely be dismissed as sampling error (Figure 10-12).

Table 8 – Descriptive Statistics Per Season and Size of Burn



	Burn Area	Time Elapsed	N	Nymph Density (per 100m)	Adult Density (per 100m)	Temperature (°C)	Relative Humidity (%)	Canopy Cover (%)	Understory Density (%)	Leaf Litter Depth (cm)
				Mean (Standard Deviation)						
Summer	Small (<200 ac)	any	24	2.13 (2.86)	0.17 (0.38)	25.65 (2.96)	45.09 (7.10)	41.67 (30.70)	42.29 (24.36)	1.23 (1.47)
	Large (>200 ac)	any	12	3.17 (5.08)	0.17 (0.39)	27.05 (4.81)	38.20 (8.39)	31.67 (28.07)	28.33 (31.50)	1.17 (1.40)
	Small (<200 ac)	>2 yr	6	5.17 (4.17)	0.17 (0.41)	23.38 (0.90)	49.57 (3.03)	61.67 (14.38)	62.50 (30.29)	2.50 (1.48)
	Large (>200 ac)	>2 yr	3	11.33 (2.52)	0.33 (0.58)	19.80 (0.66)	50.07 (2.12)	73.33 (5.77)	15.00 (8.66)	2.67 (0.76)
Fall	Small (<200 ac)	any	24	0 (0)	2.46 (2.69)	19.66 (1.62)	47.01 (6.18)	40.21 (25.77)	37.92 (17.93)	3.69 (2.30)
	Large (>200 ac)	any	12	0 (0)	2.00 (2.59)	19.89 (3.21)	46.33 (13.25)	30.00 (23.26)	35.83 (28.43)	3.29 (2.07)
	Small (<200 ac)	>2 yr	6	0 (0)	4.83 (3.66)	18.52 (1.19)	50.37 (2.99)	60.83 (18.00)	45.00 (22.58)	5.67 (1.37)
	Large (>200 ac)	>2 yr	3	0 (0)	4.33 (3.21)	14.90 (0.70)	66.33 (5.09)	58.33 (25.66)	36.67 (23.09)	6.00 (1.00)

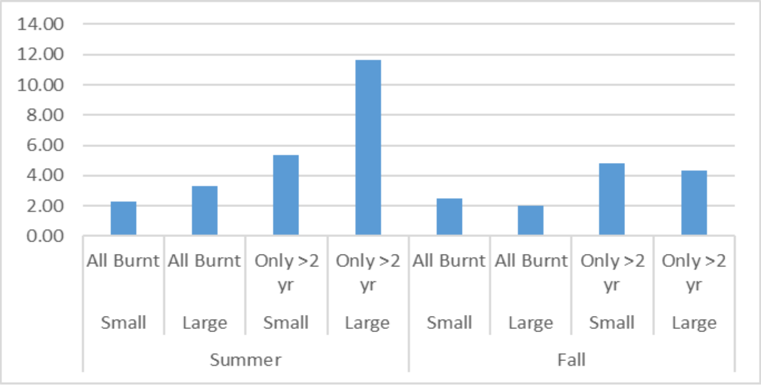


Figure 10 – Chart of Mean Tick Densities Per Season and Size of Burn

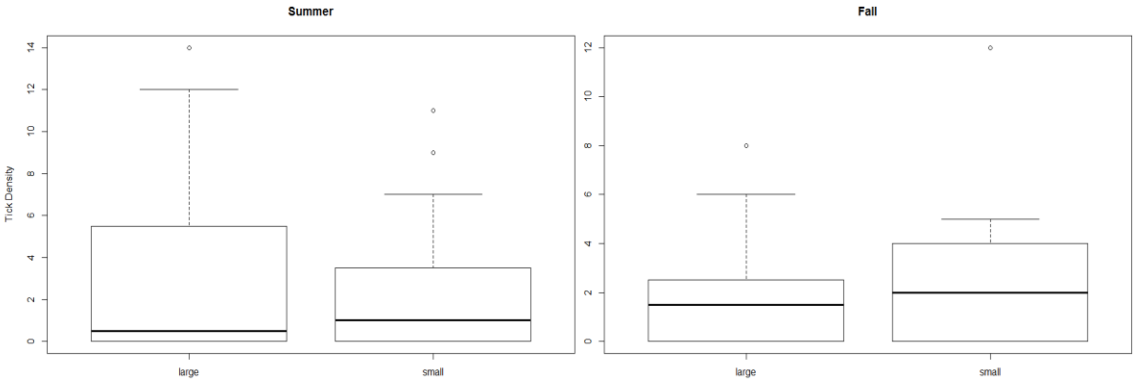


Figure 11 – Boxplots of Tick Densities Per Season and Size of Burn

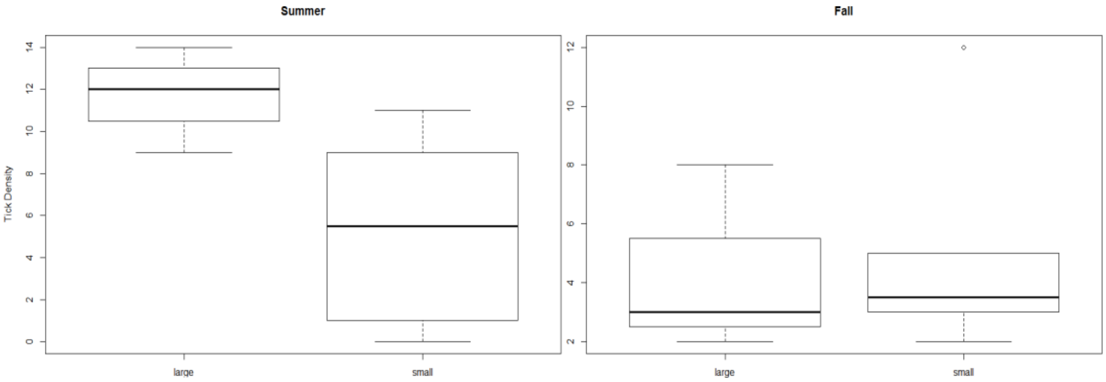


Figure 12 – Boxplots of Tick Densities in Units Burnt >2 Years Prior Per Season and Size of Burn

Table 9 – Correlation per Season between Tick Densities and Burn Unit Area

	R	df	P-Value
Summer	-0.09500613	34	*0.5815*
Fall	-0.2777347	34	*0.101*

A weak and statistically insignificant (p=0.5815) negative correlation exists between burn unit area and tick densities in the summer with an r-value of -0.095. A marginally stronger negative correlation between burn unit area and tick densities is nearly significant (p=0.101) for the fall data with an r-value of -0.277 (Table 9). ANOVA tests show no significant differences (p=0.45,0.629) in the means of tick densities between burn units smaller and larger than 200 acres for either season and that size accounts for very little (η^2=0.017, 0.001) of the variation regardless (Tables 10 & 11). Results are even less significant (p=0.847) and explain little (η^2=0.040) of the variation for the fall data when you exclude data from units burnt less than three years ago (Table 13). The ANOVA test on summer means from units burnt over two years ago returns a nearly significant (p=0.0584) result with notable (η^2=0.422) explanatory power but the total sample size of just nine likely precludes any possible extrapolation of this data (Table 12).

Table 10 –ANOVA Test of Summer Tick Densities of Small and Large Size Classes

	df	**Sum of Squares**	**Mean Square**	**F-Value**	**P-Value**	**Eta Squared**
Size Classes	1	8.7	8.681	0.584	*0.45*	0.017
Error	34	505.6	14.871			
Total	35	514.3				

Table 11 –ANOVA Test of Fall Tick Densities of Small and Large Size Classes

	df	**Sum of Squares**	**Mean Square**	**F-Value**	**P-Value**	**Eta Squared**
Size Classes	1	1.68	1.681	0.238	*0.629*	0.001
Error	34	239.96	7.058			
Total	35	241.64				

Table 12 –ANOVA Test of Summer Tick Densities of Both Size Classes,
Excluding Units Burnt ≤2 Years Prior

	df	Sum of Squares	Mean Square	F-Value	P-Value	Eta Squared
Size Classes	1	80.22	80.22	5.105	*0.0584*	0.422
Error	7	110	15.71			
Total	8	190.22				

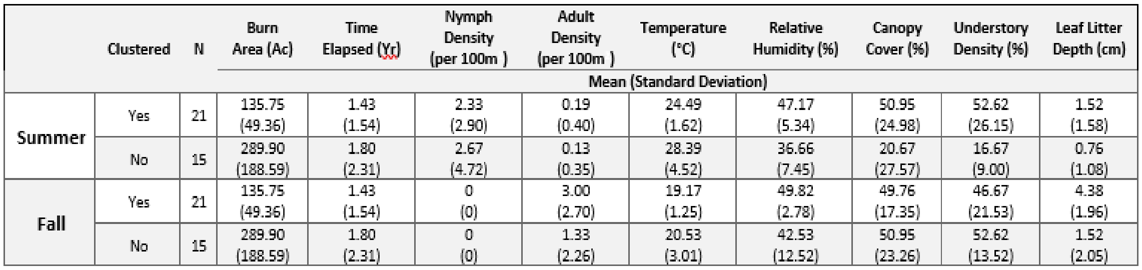
Table 13 –ANOVA Test of Fall Tick Densities of Both Size Classes,
Excluding Units Burnt ≤2 Years Prior

	df	Sum of Squares	Mean Square	F-Value	P-Value	Eta Squared
Size Classes	1	0.5	0.5	0.04	*0.847*	0.040
Error	7	12.5	12.5			
Total	8	13				

Hypothesis 3

Evaluation of the hypothesis that repeated burning throughout an area creates longer lasting deer tick reductions requires the examination of the data broken down into classes of units clustered together and units more isolated within unburnt areas. Environmental conditions are not strongly influenced by burn clustering in this timespan and do not exhibit any notable patterns (Table 14). Summer tick density means were very similar in clustered and unclustered units. Fall clustered units' density mean is more than twice that of unclustered units although the mean values are both small, the sample size is small, and variance is comparatively large (Figure 13-14).

Table 14 – Descriptive Statistics Per Season and Clustering of Burns



	Clustered	N	Burn Area (Ac)	Time Elapsed (Yr)	Nymph Density (per 100m)	Adult Density (per 100m)	Temperature (°C)	Relative Humidity (%)	Canopy Cover (%)	Understory Density (%)	Leaf Litter Depth (cm)
			Mean (Standard Deviation)								
Summer	Yes	21	135.75 (49.36)	1.43 (1.54)	2.33 (2.90)	0.19 (0.40)	24.49 (1.62)	47.17 (5.34)	50.95 (24.98)	52.62 (26.15)	1.52 (1.58)
	No	15	289.90 (188.59)	1.80 (2.31)	2.67 (4.72)	0.13 (0.35)	28.39 (4.52)	36.66 (7.45)	20.67 (27.57)	16.67 (9.00)	0.76 (1.08)
Fall	Yes	21	135.75 (49.36)	1.43 (1.54)	0 (0)	3.00 (2.70)	19.17 (1.25)	49.82 (2.78)	49.76 (17.35)	46.67 (21.53)	4.38 (1.96)
	No	15	289.90 (188.59)	1.80 (2.31)	0 (0)	1.33 (2.26)	20.53 (3.01)	42.53 (12.52)	50.95 (23.26)	52.62 (13.52)	1.52 (2.05)

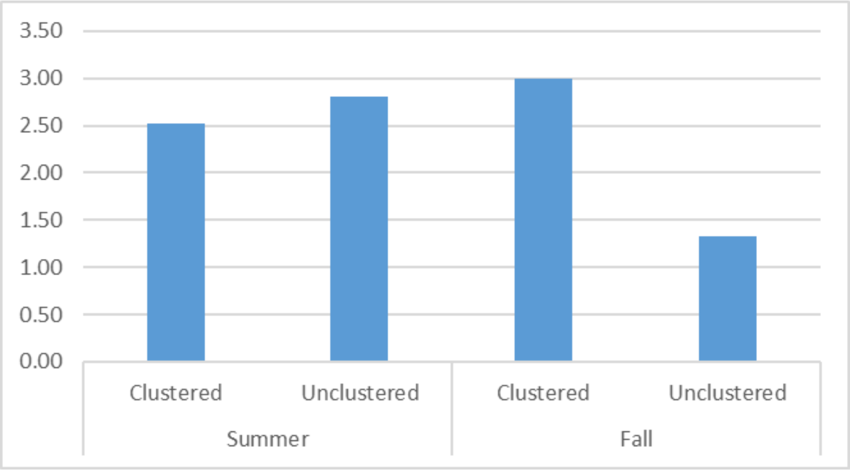


Figure 13 – Chart of Mean Tick Densities per Season and Clustering of Burns

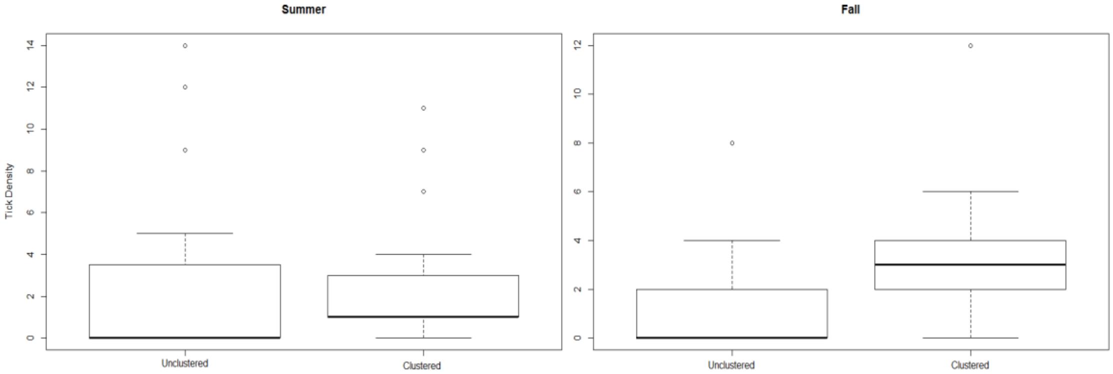


Figure 14 – Boxplots of Tick Densities Per Season and Clustering of Burns

ANOVA tests show no significant difference (p=0.835) in the means of summer tick densities between clustered and unclustered units. Very little (η^2=0.001) of the variation between categories can be accounted for either (Table 15). ANOVA tests on fall tick density means return a nearly significant (p=0.0595) result with some explanatory power (η^2=0.101) but the small sample size leaves much room for error or the influence of other variables (Table 16).

Table 15 –ANOVA Test of Summer Tick Densities in Clustered and Unclustered Burn Units

	df	Sum of Squares	Mean Square	F-Value	P-Value	Eta Squared
Clustering	1	0.7	0.667	0.044	*0.835*	0.001
Error	34	513.6	15.107			
Total	35	514.3				

Table 16 –ANOVA Test of Fall Tick Densities in Clustered and Unclustered Burn Units

	df	Sum of Squares	Mean Square	F-Value	P-Value	Eta Squared
Clustering	1	24.31	24.306	3.802	*0.0595*	0.101
Error	34	217.33	6.392			
Total	35	241.64				

Hypothesis 4

Evaluation of the hypothesis that fire characteristics are the primary determinants of deer tick density in areas undergoing prescribed fire management and that ecological and climatic factors are secondary requires the careful construction and evaluation of multiple regression models that include all key independent variables. A model constructed with data from the 42 summer samples with three categorical time classes was determined to be statistically significant ($p<0.00001$) and explain over 84% of the variation in the data. Time classes had predictable effects with unburnt patches increasing (COEFF=0. 23775) tick density predictions and recent burns decreasing (COEFF=-0. 19131) predictions. The temporally distant burn category is incorporated into the intercept. Burn area had a slight positive effect but was very insignificant ($p=0.53098$). This model predicts that increasing temperature, canopy cover, and understory density would decrease tick densities. Increasing leaf litter depth and relative humidity are predicted to increase tick densities. Burn area, canopy cover, and understory density all had effects that are counter to expectations. Burn area and relative humidity are the only two variables deemed insignificant in this model and temperature, relative humidity, and canopy cover all had high collinearity (Table 17).

Table 17 – Scaled Regression Model for Summer Tick Densities
with Time Classed into Recent, Distant, and Unburnt

	Coefficient	**Standard Error**	**T-Value**	**P-Value**	**VIF**
Intercept	0.59150	0.19881	2.975	*0.00544*	-
Unburnt	0.23775	0.07506	3.167	*0.00331*	3.85
Recent Burn	-0.19131	0.05367	-3.564	*0.00114*	3.85
Burn Area	0.04392	0.06936	0.633	*0.53098*	1.48
Temperature	-0.43452	0.20774	-2.092	*0.04425*	12.0
Relative Humidity	0.18288	0.14994	1.220	*0.23123*	6.39
Canopy Cover	-0.34984	0.13651	-2.563	*0.01513*	7.20
Understory Density	-0.25382	0.07639	-3.323	*0.00219*	2.04
Leaf Litter Depth	0.37910	0.12465	3.041	*0.00459*	3.97
Residual Error= 0.1092	**F-statistic=** 28.43	**Adj R-squared=** 0.8426	**Model P-Value=** *<0.00001*		

A model constructed with data from the 42 fall samples with three categorical time classes was determined to be statistically significant (p=0.00003) and explain over 52% of the variation in the data. Time classes had predictable effects with unburnt patches increasing (COEFF=0.273919) tick density predictions and recent burns decreasing (COEFF=-0.104739) predictions although it was not statistically significant (p=0.2695). The temporally distant burn category is incorporated into the intercept. Burn area had a slight positive effect but was very insignificant (p=0.9593). This model predicts that increasing temperature and relative humidity would decrease tick densities. Increasing canopy cover, understory density, and leaf litter depth are predicted to increase tick densities. Burn area and relative humidity had effects that are counter to expectations. The unburnt time class is the only variable deemed significant in this model and temperature and relative humidity had high collinearity (Table 18).

Table 18 – Scaled Regression Model for Fall Tick Densities
with Time Classed into Recent, Distant, and Unburnt

	Coefficient	**Standard Error**	**T-Value**	**P-Value**	**VIF**
Intercept	0.175852	0.248948	0.706	*0.4849*	-
Unburnt	0.273919	0.120020	2.282	*0.0291*	3.38
Recent Burn	-0.104739	0.093265	-1.123	*0.2695*	3.38
Burn Area	0.005554	0.108034	0.051	*0.9593*	1.31
Temperature	-0.086168	0.284639	-0.303	*0.7640*	5.69
Relative Humidity	-0.083525	0.317548	-0.263	*0.7942*	7.34
Canopy Cover	0.164617	0.153126	1.075	*0.2902*	3.37
Understory Density	0.110604	0.140717	0.786	*0.4375*	2.17
Leaf Litter Depth	0.115548	0.172556	0.670	*0.5078*	2.77
Residual Error= 0.1809	**F-statistic=** 6.686	**Adj R-squared=** 0.5259	**Model P-Value=** *0.00003*		

A model constructed with data from the 36 summer samples from units that were burnt was determined to be statistically significant (p<0.00001) and explain over 80% of the variation in the data. Increasing time since burn has a strong positive effect (COEFF=0.61574) on tick densities in this model. Burn area had a slight positive effect but was insignificant (p=0.23067). This model predicts that increasing temperature, canopy cover, and understory density would decrease tick densities. Increasing relative humidity and leaf litter depth are predicted to increase tick densities. Burn area, canopy cover, and understory density had effects that are counter to expectations. Time elapsed, relative humidity, and understory density are the only variables deemed significant in this model and temperature and canopy cover had high collinearity (Table 19).

Table 19 – Scaled Regression Model for Summer Tick Densities
with Unburnt Plots Excluded

	Coefficient	**Standard Error**	**T-Value**	**P-Value**	**VIF**
Intercept	0.00521	0.23240	0.022	*0.98227*	-
Time Elapsed	0.61574	0.10478	5.876	*<0.00001*	2.55
Burn Area	0.10147	0.08281	1.225	*0.23067*	1.68
Temperature	-0.10203	0.23720	-0.430	*0.67038*	10.9
Relative Humidity	0.30694	0.14596	2.103	*0.04459*	4.93
Canopy Cover	-0.08141	0.16236	-0.501	*0.61999*	7.74
Understory Density	-0.25855	0.08637	-2.993	*0.00571*	1.64
Leaf Litter Depth	0.07593	0.13452	0.564	*0.57698*	3.51
Residual Error= 0.1212	**F-statistic=** 21.53	**Adj R-squared=** 0.8042	**Model P-Value=** *<0.00001*		

A model constructed with data from the 36 fall samples from units that were burnt was determined to be statistically significant (p=0.003285) and explain over 38% of the variation in the data. Increasing time since burn has a strong positive effect (COEFF=0.376817) on tick densities in this model. Burn area had a slight negative effect but was very insignificant (p=0.6650). This model predicts that increasing relative humidity would decrease tick densities. Increasing temperature, canopy cover, understory density, and leaf litter depth are predicted to increase tick densities. Temperature and relative humidity had effects that are counter to expectations. Time elapsed and canopy cover are the only variables deemed significant in this model and temperature and relative humidity had high collinearity (Table 20).

Table 20 – Scaled Regression Model for Fall Tick Densities with Unburnt Plots Excluded

	Coefficient	**Standard Error**	**T-Value**	**P-Value**	**VIF**
Intercept	-0.043471	0.293231	-0.148	*0.8832*	-
Time Elapsed	0.376817	0.139436	2.702	*0.0116*	2.24
Burn Area	-0.045683	0.104385	-0.438	*0.6650*	1.32
Temperature	0.085199	0.320524	0.266	*0.7923*	7.83
Relative Humidity	-0.341424	0.319337	-1.069	*0.2941*	7.52
Canopy Cover	0.394284	0.157612	2.502	*0.0185*	3.29
Understory Density	0.007295	0.114574	0.064	*0.9497*	1.48
Leaf Litter Depth	0.128800	0.174120	0.740	*0.4656*	2.41
Residual Error= 0.1721	**F-statistic=** 4.094	**Adj R-squared=** 0.3822	**Model P-Value=** *0.003285*		

DISCUSSION

Significance of these Results

The importance of the results of this pilot study lies in the broad generalizations that can be inferred and not necessarily in the specific details. Some relationships are clearer in the data than others and the various limitations encountered in this process likely cloud the subtler patterns that may be present. While these limitations may be better accounted for and corrected in future iterations of this research, the results of this attempt still illuminate key facets of the potential for use of prescribed fire in deer tick management.

Hypothesis 1

Although the small sample sizes for unburnt units and units burnt over two years prior weaken the strength of the ANOVA test results, the clearly identifiable patterns of means and the statistical significance and size effects of all the tests aligns well with expectations. Tick densities fall dramatically with prescribed fire and mean densities several years after burning were approximately half that of unburnt areas (Table 2). ANOVA tests suggested that these means are statistically different from each other and that time is the primary reason for this difference (Tables 6 & 7). This is cause to reject the null hypothesis (Ho1) that deer tick reductions from prescribed burning do not persist longer than two years from when the burn was conducted. The alternative hypothesis (Ha1) that deer tick reductions from prescribed burning persist longer than two years is then accepted. It is likely that the environmental changes resultant of prescribed fire is dramatic and long-lasting enough to partially inhibit deer tick re-establishment and/or population growth.

Hypothesis 2

There is no obvious pattern in the data between different size classes and the ANOVA tests confirm that there is no significant difference in their means and that very little variation between these classes could be explained by unit sizes (Tables 8-13). This is counter to the expectation that larger burn units would exhibit smaller tick densities than smaller units. The small sample size likely masks any role areal size may play in inhibiting tick recolonization post-burn. This would be especially true when examining just the nine samples per season from units burnt over two years ago. The burn area effect may be too subtle to be discernible in these conditions. The burn units in this study area may also be too small for burn area to have a notable effect on tick recolonization. Prescribed burns in other regions can be up to thousands of acres each (Gleim et al. 2014). The inherent complexity of ecosystems and the habitat heterogeneity within and between burn units in the study area could play a role in obscuring a potential burn area effect as well. Spatial autocorrelation is likely occurring between the repopulating tick densities of isolated burnt units and the densities in adjacent areas. This may have resulted in inflated densities in some larger units which would counter the effect of increasing burn sizes. Assuming it exists, any number of these possibilities could explain the lack of a size effect in the data. The null hypothesis (Ho2) that there is no relationship between deer tick density and the size of the area burned is, therefore, unable to be rejected. The alternative hypothesis (Ha2) that prescribed burning creates longer lasting reductions in deer tick density as the size of the area burned is increased is then rejected for this pilot study.

Hypothesis 3

Although mapping indicated otherwise, there is no clear difference between the tick density means of clustered and unclustered units (Figures 4-7). Summer densities are nearly the same between categories and fall densities are counter to the expectation that clustered units would exhibit fewer ticks than unclustered units. This difference is still not particularly notable because the clustered mean is equal to the mean of all fall samples at three ticks per hundred square meters and far less than the highest recorded value of fourteen (Tables 14 & 22). This discrepancy may be due to sampling error or even the influence of much shallower leaf litter depths in fall's unclustered units. ANOVA tests comparing these means reinforce these observations. There is no significant difference in the tick density means from summer and the difference is just nearly significant in fall. Further, little variation between these classes could be explained by clustering (Tables 15-16). The sample sizes are large enough to not weaken the ANOVA test results but may yet be too small to demonstrate any effect burn unit clustering may have on post-burn tick re-establishment and survival. Like the burn area effect, the clustering effect may be too subtle to be discernible in these conditions if it does exist. Prescribed fire may also still be too new of a practice in the study area for burn clustering to be widespread enough to influence tick populations. Entire landscapes in other regions have been under prescribed fire management long enough that nearly every patch has been burnt more than once (Gleim et al. 2014). Burning of that spatial and temporal extent may be necessary for clustering to affect tick densities. Finally, the inherent complexity of ecosystems and the habitat heterogeneity within and between burn units in the study area may also play a role in obscuring a potential clustering effect. The null hypothesis (Ho3) that repeated burning throughout an area does not alter the duration of resultant deer tick reductions is, therefore, unable to be rejected. The alternative hypothesis (Ha3) that repeated burning throughout an area creates longer lasting deer tick reductions is then rejected for this pilot study.

Hypothesis 4

It is difficult to create accurate regression models of ecological systems because of the inherent interrelatedness of each part and process in an ecosystem. Even accounting for multicollinearity between variables does not ensure an accurate model. Undetected interactions within the data or effects of variables not included in the study may be important determinants of the dependent variable. It is unlikely that any of the models constructed from the summer and fall data are truly accurate and may just be broadly suggestive at best. The relatively small sample sizes used to construct these models further lowers their reliability. Nonetheless, some useful information can be gleaned from their examination.

The data used to construct each model per season is identical other than whether time was categorized and if unburnt unit samples were included. Variation between summer and fall is expected but the effects of each factor governing deer tick densities should still largely be the same. The variation of these effects between models does not reflect these expectations. Furthermore, variables are often predicted to have opposite effects in different models. The only variable with nearly consistent predicted effects and statistical significance in each model is time. Tick density post-burn is strongly governed by time elapsed since burn, and densities in units that are unburnt, recently burnt, and burnt more than two years prior are distinct from each other within the influence of every other variable (Tables 17-20). This aligns well with the expectation that burn characteristics are key determinants of tick densities. Burn sizes are neither consistent nor significant in any of the models, however, and this runs counter to expectations. This may be due to the same reasons addressed for the lack of a burn area effect in hypothesis two. The unreliability of these models and that, at most, only one burn characteristic may be important in this data force a rejection of the alternative hypothesis (Ha4) that fire characteristics are the primary determinants of deer tick density in areas undergoing prescribed fire management and ecological and climatic factors are secondary. The null hypothesis (Ho4) that ecological or climatic factors are the primary determinants of deer tick densities in areas undergoing prescribed fire management and fire characteristics are secondary is then not rejected. The most important determinants of deer tick densities in areas under fire management are left undetermined by this study.

Limitations of this Study

The purpose of a pilot study is to test the feasibility of the research design and identify the shortcomings and missteps that can be corrected or better accounted for in future iterations of the study. This study was successful in these goals and generated enough positive results to incentivize pursuit of these future iterations.

Some of the limitations of this study were foreseen but unavoidable due to temporal and/or fiscal constraints. Many other limitations were made apparent during or after the fieldwork was conducted and could not be corrected in this analysis. The most apparent limitation of this study is that the data collected is only from one year.

Temporal variation within each burn unit is wholly unaccounted for so that time's effect is approximated by comparing different units that have been burnt at different times. The effect of spatial variation between units was accounted for as best as possible through the ecological and climatic variables but this is an imperfect measurement of change over time. Additionally, prescribed fire at these sites only began six years prior to this study's data collection. Longer term changes cannot be determined without longer term data. It is unknown if or when the measured characteristics would eventually return to pre-burn levels.

Some key data is missing from this analysis. Most importantly, rodent and white-tailed deer population densities are not included in the datasets. Rodent density estimations generally require a large amount of expensive equipment and a considerable investment of labor and time. While not feasible in this study, this information is important for understanding rodents' potentially large effect on the relationship between ticks and fire. Deer density effects on post-fire tick colonization and reproduction are likely important but are labor intensive and/or expensive to measure. Additionally, elevation and slope were not included but may be important in the post-fire regeneration of burn units and could account for some of the unexplained variation.

The data analysis revealed more shortcomings in the study design and data collection process. Canopy cover, understory density, and soil type were all visually approximated. Precise measurement of these variables is too time and labor intensive for the constraints of this study but important differences between sample plots may have been overlooked. Additionally, Game Lands 033 and 176 are quite different ecologically and may not be easily comparable. The ridgetop pine barrens of 033 likely develop differently post-fire than the oak barrens at average elevations that make up most of 176. Trends may have been more clear in one area but made indiscernible by inclusion of data from the other area. The sample size is likely the most serious limitation of this study, however. The fieldwork was more time and labor intensive than expected and thus fewer samples were taken than were initially planned. This was most detrimental in limiting the control sites to one unit per study area. Categorizations based on time, size, and clustering that were used to test the first three hypotheses were not fully determined prior to the fieldwork which led to some being woefully small. This then precluded the reliability of many of the statistical tests. Finally, the sample size is also too small in regards to burn units in the landscape. This is largely due to the recentness prescribed fire use in these areas but also likely a consequence of the Pennsylvania Game Commission's annual budgeting constraints. More burn units throughout the study areas would allow a more thorough examination of the effects that size and clustering have on tick re-establishment and population growth post-burn. Accounting for these limitations in an expanded version of this study may build upon the existing evidence supporting prescribed fire for deer tick management and help elucidate the many remaining uncertainties.

Areas of Future Research

Iteration of this Study

With adequate funding and a team of research assistants, a revised study design could easily address every issue identified with the pilot study. Annual data collection over several years would give a more accurate representation of how these factors change over time.

Host densities can be incorporated into the dataset as well. The best method of measuring rodent densities is with live-trapping. Devices such as the Sherman trap can be purchased, baited and then strategically laid out in the study areas and checked regularly to estimate rodent populations. Deer populations can be approximated with scat counts in study plots, passive surveying with carefully placed infrared cameras, or with aerial infrared photography. One or more of these methods could be incorporated with assistants and the proper equipment. Digital elevation models (DEM) could be acquired and manipulated in GIS software to determine exact elevation and slope of sampling sites if a handheld GPS is used to record the coordinates. More precise measurement methods for canopy cover, understory density, and soil type can be taken from the literature and incorporated into the methodology.

Lastly, the oak dominance, average elevation, and longer burn history of Game Lands 176 make it the area more easily generalized to the rest of the Northeast and should be the sole site of future iterations of this study. The burn units in this area should be more intensively and strategically sampled to ensure a vast dataset is accrued during each season of fieldwork and that sample sizes per control data and each time, size, and clustering category are adequate for the intended statistical tests.

Future Development of this Research

The revised version of this study should be repeated in other locations throughout the Northeast and Midwest with common ecosystem types that are infested with deer ticks and Lyme disease. A uniform methodology shared between each study would allow comparison of the respective results and possibly the construction of a generalizable model that can predict the effectiveness of a prescribed burning strategy for deer tick management in any given area.

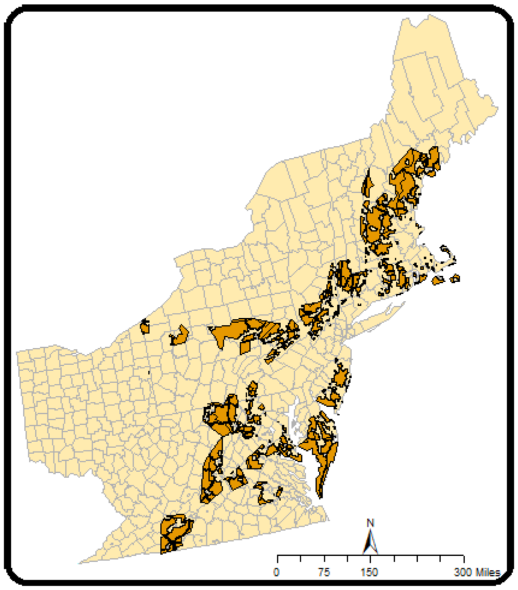


Figure 15 - Map of Potential Study Sites for Initial Examinations of the Relationship between Prescribed Fire and Deer Tick Range Expansion
(based on data from the CDC, EPA, & the U.S. Census Bureau)

Further research can then investigate the effectiveness of prescribed fire on managing the dispersal and range expansion of the deer tick. Initial research should focus on areas of oak and pine forest that tend to have high fire suitability and are within the established range of the deer tick but far enough away from metropolitan areas and major roadways as to not present a safety hazard (Figure 11). Extensive fire corridors could be set up and carefully monitored to examine rates of dispersal through and into these areas. Factors affecting success could be identified, used to inform further research, and incorporated into strategies for slowing the range expansion.

CONCLUSION

The complexity of ecological systems makes it difficult to isolate any single interaction within that system. This is especially true in the examination of deer ticks and fire. This pilot study gave few satisfying answers but instead built upon prior research to create a solid framework that may eventually illuminate this relationship. While it is yet unclear whether the size and spatial distribution of prescribed fires strongly influence the longevity of deer tick reductions, this study has demonstrated that populations may remain significantly lower than pre-burn levels even several years after the burn was conducted in at least some areas. It is also still undetermined whether burning overwhelms the ecological and climatic characteristics determinant of overall habitat suitability and potential deer tick densities. Hopefully future iterations of this research will uncover if prescribed fires of a size and frequency typical of real-world management alter environmental conditions enough to maintain reduced tick populations long after the ecosystem has recovered.

Implications for Management

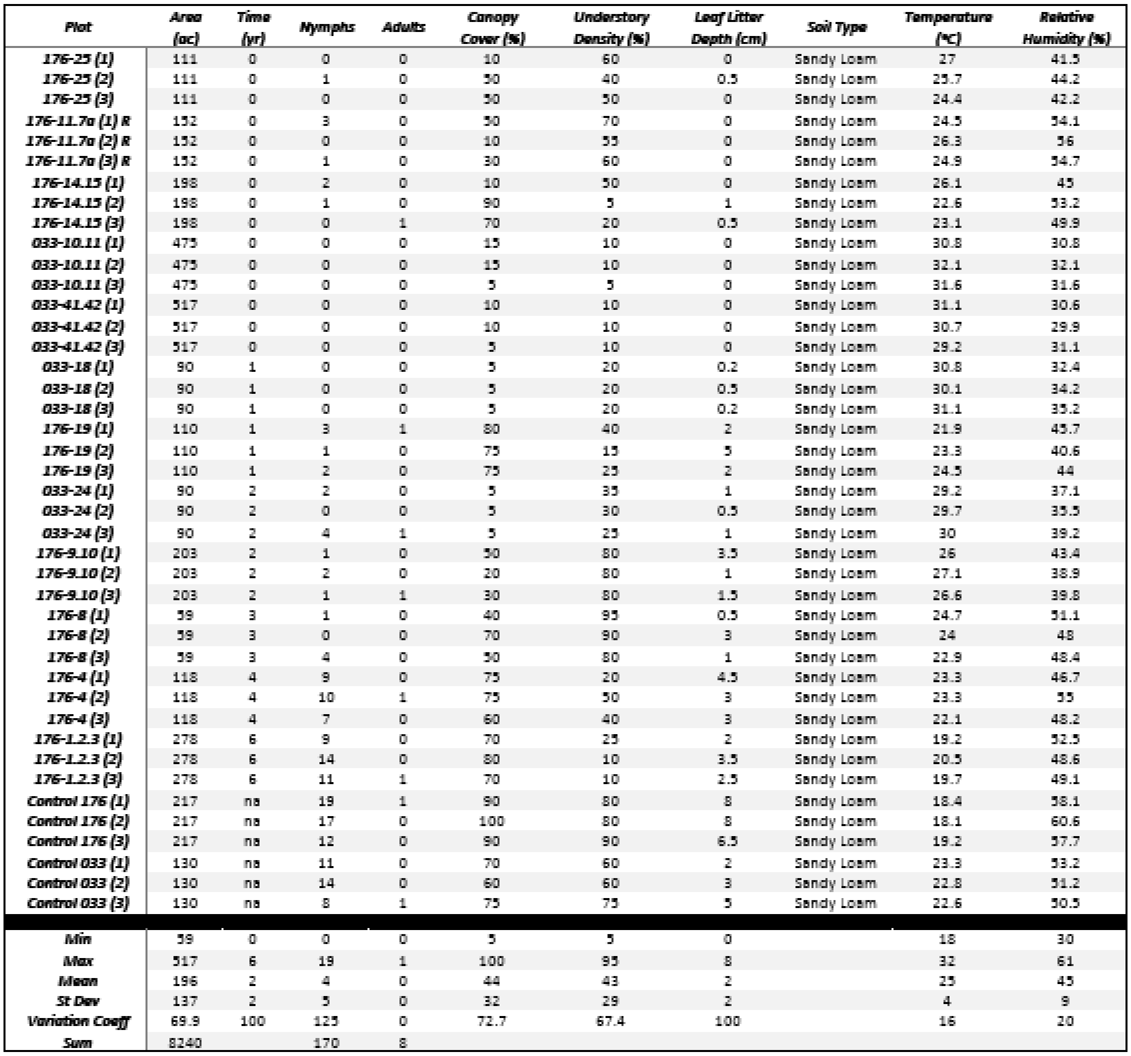
This study may be the first step in showing that if burning changes most of a landscape into unsuitable habitat then host presence will not necessarily facilitate re-establishment. Densities could remain near zero if subsequent colonizations have low probabilities of survival and reproduction. This by itself will not stop dispersals through areas but these areas will no longer provide source populations for the ticks' ongoing geographic range expansion.

Agencies already managing lands with prescribed fire, such as the Pennsylvania Game Commission or the Albany Pine Bush Preserve, could incorporate tick control into their yearly burning goals. Fire plans could be altered to maximize tick reduction longevity per burn and potentially destabilize tick metapopulations throughout their respective managed lands. Further, use of prescribed fire could be more easily justified to the public when faced with its potential for reducing Lyme disease risk. More funding to these agencies may even be made available if the direct benefits to the public from prescribed fire are emphasized. More agencies successfully carrying out these strategies and increasing their funding and public attention could be instrumental for instigating region-level action for Lyme disease control with prescribed fire and its surrogate strategies.

Burning is more valuable than mechanical or chemical strategies because of its immediate tick density reduction but all three are integral tools in ecological restoration and tick management. These other methods can effectively emulate burning’s key long-term ecological effects in areas where fires are too dangerous or when lingering societal fears over its destructive ability block its use. As more parts of the Northeast adopt these strategies into their environmental management plans, tick densities and Lyme risk over large areas may be reduced. Large swaths of unsuitable habitat will make successful dispersals less likely and the expanding extent of this crisis may be slowed or even reversed. Zones of the built environment with high Lyme disease risk may then no longer be bordered by infested natural areas that act as source populations for the ticks responsible for most human cases. It is likely that humans will never be able to reduce deer tick distributions back to their endemic ranges but we can learn to manage their populations to minimize Lyme disease risk.

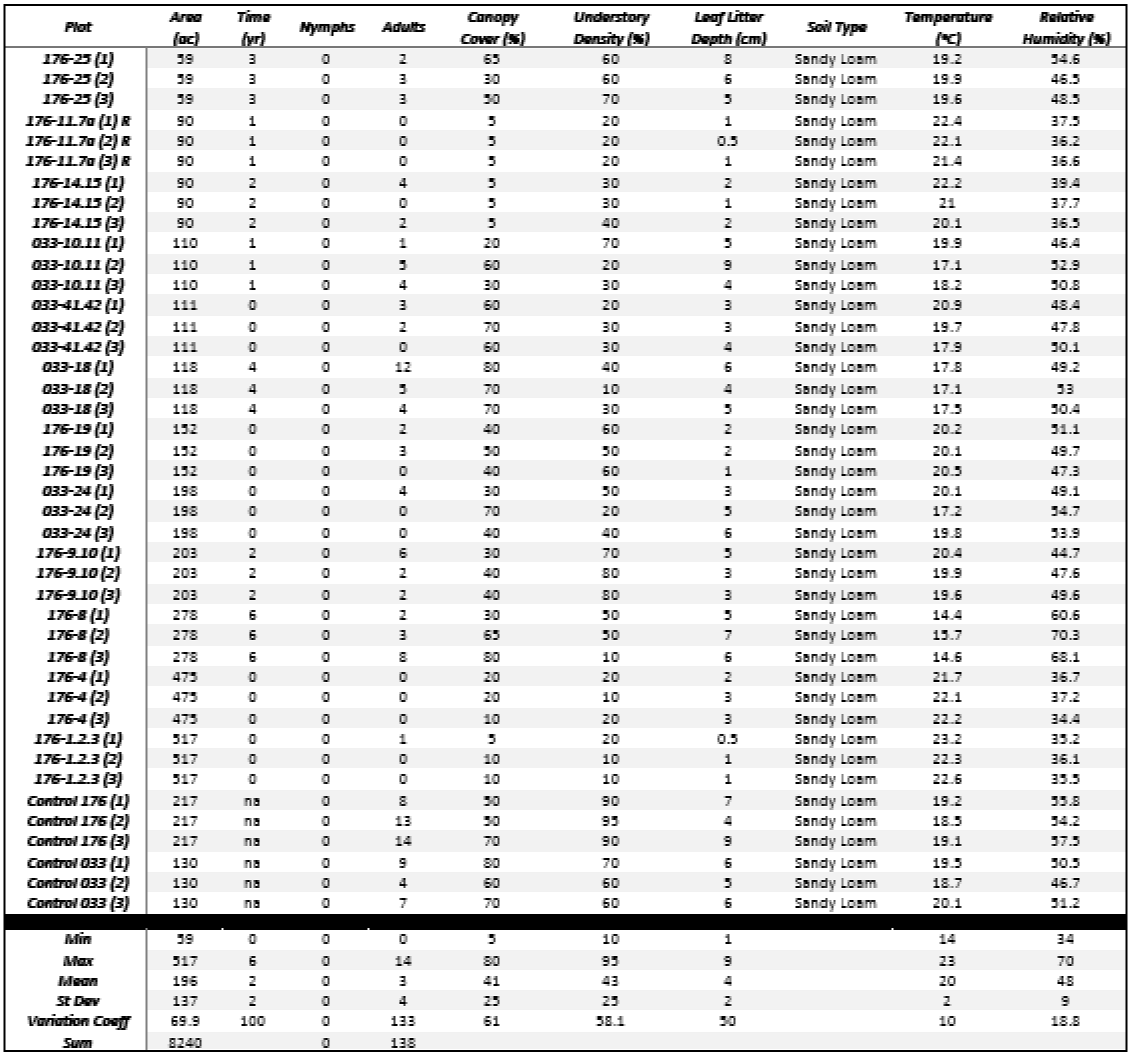
APPENDIX

Table 21 – Raw Summer Data



Plot	Area (ac)	Time (yr)	Nymphs	Adults	Canopy Cover (%)	Understory Density (%)	Leaf Litter Depth (cm)	Soil Type	Temperature (°C)	Relative Humidity (%)
176-25 (1)	111	0	0	0	10	60	0	Sandy Loam	27	41.5
176-25 (2)	111	0	1	0	50	40	0.5	Sandy Loam	25.7	44.2
176-25 (3)	111	0	0	0	50	50	0	Sandy Loam	24.4	42.2
176-11.7a (1) R	152	0	3	0	50	70	0	Sandy Loam	24.5	54.1
176-11.7a (2) R	152	0	0	0	10	55	0	Sandy Loam	26.3	56
176-11.7a (3) R	152	0	1	0	30	60	0	Sandy Loam	24.9	54.7
176-14.15 (1)	198	0	2	0	10	50	0	Sandy Loam	26.1	45
176-14.15 (2)	198	0	1	0	90	5	1	Sandy Loam	22.6	53.2
176-14.15 (3)	198	0	0	1	70	20	0.5	Sandy Loam	23.1	49.9
033-10.11 (1)	475	0	0	0	15	10	0	Sandy Loam	30.8	30.8
033-10.11 (2)	475	0	0	0	15	10	0	Sandy Loam	32.1	32.1
033-10.11 (3)	475	0	0	0	5	5	0	Sandy Loam	31.6	31.6
033-41.42 (1)	517	0	0	0	10	10	0	Sandy Loam	31.1	30.6
033-41.42 (2)	517	0	0	0	10	10	0	Sandy Loam	30.7	29.9
033-41.42 (3)	517	0	0	0	5	10	0	Sandy Loam	29.2	31.1
033-18 (1)	90	1	0	0	5	20	0.2	Sandy Loam	30.8	32.4
033-18 (2)	90	1	0	0	5	20	0.5	Sandy Loam	30.1	34.2
033-18 (3)	90	1	0	0	5	20	0.2	Sandy Loam	31.1	35.2
176-19 (1)	110	1	3	1	80	40	2	Sandy Loam	21.9	45.7
176-19 (2)	110	1	1	0	75	15	5	Sandy Loam	23.3	40.6
176-19 (3)	110	1	2	0	75	25	2	Sandy Loam	24.5	44
033-24 (1)	90	2	2	0	5	35	1	Sandy Loam	29.2	37.1
033-24 (2)	90	2	0	0	5	30	0.5	Sandy Loam	29.7	35.5
033-24 (3)	90	2	4	1	5	25	1	Sandy Loam	30	39.2
176-9.10 (1)	203	2	1	0	50	80	3.5	Sandy Loam	26	43.4
176-9.10 (2)	203	2	2	0	20	80	1	Sandy Loam	27.1	38.9
176-9.10 (3)	203	2	1	1	30	80	1.5	Sandy Loam	26.6	39.8
176-8 (1)	59	3	1	0	40	95	0.5	Sandy Loam	24.7	51.1
176-8 (2)	59	3	0	0	70	90	3	Sandy Loam	24	48
176-8 (3)	59	3	4	0	50	80	1	Sandy Loam	22.9	48.4
176-4 (1)	118	4	9	0	75	20	4.5	Sandy Loam	23.3	46.7
176-4 (2)	118	4	10	1	75	50	3	Sandy Loam	23.3	55
176-4 (3)	118	4	7	0	60	40	3	Sandy Loam	22.1	48.2
176-1.2.3 (1)	278	6	9	0	70	25	2	Sandy Loam	19.2	52.5
176-1.2.3 (2)	278	6	14	0	80	10	3.5	Sandy Loam	20.5	48.6
176-1.2.3 (3)	278	6	11	1	70	10	2.5	Sandy Loam	19.7	49.1
Control 176 (1)	217	na	19	1	90	80	8	Sandy Loam	18.4	58.1
Control 176 (2)	217	na	17	0	100	80	8	Sandy Loam	18.1	60.6
Control 176 (3)	217	na	12	0	90	90	6.5	Sandy Loam	19.2	57.7
Control 033 (1)	130	na	11	0	70	60	2	Sandy Loam	23.3	53.2
Control 033 (2)	130	na	14	0	60	60	3	Sandy Loam	22.8	51.2
Control 033 (3)	130	na	8	1	75	75	5	Sandy Loam	22.6	50.5
Min	59	0	0	0	5	5	0		18	30
Max	517	6	19	1	100	95	8		32	61
Mean	196	2	4	0	44	43	2		25	45
St Dev	137	2	5	0	32	29	2		4	9
Variation Coeff	69.9	100	125	0	72.7	67.4	100		16	20
Sum	8240		170	8						

Table 22 – Raw Fall Data



Plot	Area (ac)	Time (yr)	Nymphs	Adults	Canopy Cover (%)	Understory Density (%)	Leaf Litter Depth (cm)	Soil Type	Temperature (°C)	Relative Humidity (%)
176-25 (1)	59	3	0	2	65	60	8	Sandy Loam	19.2	54.6
176-25 (2)	59	3	0	3	30	60	6	Sandy Loam	19.9	46.5
176-25 (3)	59	3	0	3	50	70	5	Sandy Loam	19.6	48.5
176-11.7a (1) R	90	1	0	0	5	20	1	Sandy Loam	22.4	37.5
176-11.7a (2) R	90	1	0	0	5	20	0.5	Sandy Loam	22.1	36.2
176-11.7a (3) R	90	1	0	0	5	20	1	Sandy Loam	21.4	36.6
176-14.15 (1)	90	2	0	4	5	30	2	Sandy Loam	22.2	39.4
176-14.15 (2)	90	2	0	0	5	30	1	Sandy Loam	21	37.7
176-14.15 (3)	90	2	0	2	5	40	2	Sandy Loam	20.1	36.5
033-10.11 (1)	110	1	0	1	20	70	5	Sandy Loam	19.9	46.4
033-10.11 (2)	110	1	0	5	60	20	9	Sandy Loam	17.1	52.9
033-10.11 (3)	110	1	0	4	30	30	4	Sandy Loam	18.2	50.8
033-41.42 (1)	111	0	0	3	60	20	3	Sandy Loam	20.9	48.4
033-41.42 (2)	111	0	0	2	70	30	3	Sandy Loam	19.7	47.8
033-41.42 (3)	111	0	0	0	60	30	4	Sandy Loam	17.9	50.1
033-18 (1)	118	4	0	12	80	40	6	Sandy Loam	17.8	49.2
033-18 (2)	118	4	0	5	70	10	4	Sandy Loam	17.1	53
033-18 (3)	118	4	0	4	70	30	5	Sandy Loam	17.5	50.4
176-19 (1)	152	0	0	2	40	60	2	Sandy Loam	20.2	51.1
176-19 (2)	152	0	0	3	50	50	2	Sandy Loam	20.1	49.7
176-19 (3)	152	0	0	0	40	60	1	Sandy Loam	20.5	47.3
033-24 (1)	198	0	0	4	30	50	3	Sandy Loam	20.1	49.1
033-24 (2)	198	0	0	0	70	20	5	Sandy Loam	17.2	54.7
033-24 (3)	198	0	0	0	40	40	6	Sandy Loam	19.8	53.9
176-9.10 (1)	203	2	0	6	30	70	5	Sandy Loam	20.4	44.7
176-9.10 (2)	203	2	0	2	40	80	3	Sandy Loam	19.9	47.6
176-9.10 (3)	203	2	0	2	40	80	3	Sandy Loam	19.6	49.6
176-8 (1)	278	6	0	2	30	50	5	Sandy Loam	14.4	60.6
176-8 (2)	278	6	0	3	65	50	7	Sandy Loam	15.7	70.3
176-8 (3)	278	6	0	8	80	10	6	Sandy Loam	14.6	68.1
176-4 (1)	475	0	0	0	20	20	2	Sandy Loam	21.7	36.7
176-4 (2)	475	0	0	0	20	10	3	Sandy Loam	22.1	37.2
176-4 (3)	475	0	0	0	10	20	3	Sandy Loam	22.2	34.4
176-1.2.3 (1)	517	0	0	1	5	20	0.5	Sandy Loam	23.2	35.2
176-1.2.3 (2)	517	0	0	0	10	10	1	Sandy Loam	22.3	36.1
176-1.2.3 (3)	517	0	0	0	10	10	1	Sandy Loam	22.6	35.5
Control 176 (1)	217	na	0	8	50	90	7	Sandy Loam	19.2	55.8
Control 176 (2)	217	na	0	13	50	95	4	Sandy Loam	18.5	54.2
Control 176 (3)	217	na	0	14	70	90	9	Sandy Loam	19.1	57.5
Control 033 (1)	130	na	0	9	80	70	6	Sandy Loam	19.5	50.5
Control 033 (2)	130	na	0	4	60	60	5	Sandy Loam	18.7	46.7
Control 033 (3)	130	na	0	7	70	60	6	Sandy Loam	20.1	51.2
Min	59	0	0	0	5	10	1		14	34
Max	517	6	0	14	80	95	9		23	70
Mean	196	2	0	3	41	43	4		20	48
St Dev	137	2	0	4	25	25	2		2	9
Variation Coeff	69.9	100	0	133	61	58.1	50		10	18.8
Sum	8240		0	138						

REFERENCES

Abrams, Marc D. and Gregory J. Nowacki. 2016. An interdisciplinary approach to better assess global change impacts and drought vulnerability on forest dynamics. *Tree Physiology* 00: 1-7.

Allan, Brian F. 2009. Influence of prescribed burns on the abundance of *Amblyomma americanum* (Acari: Ixodidae) in the Missouri Ozarks. *Journal of Medical Entomology* 46(5): 1030-1036.

Arthur, Mary A. et al. 2012. Refining the oak-fire hypothesis for management of oak-dominated forests of the eastern United States. *Journal of Forestry* 110(5): 257-266.

Biesiada, Grażyna, et al. 2012. Lyme disease: review. *Arch Med Sci* 8(6): 978-82.

Blumler, Mark A. 2003. Smokey the Bear and Lyme Disease. *The Pennsylvania Geographer* 41(1): 88-105.

Botkin, Daniel B. 1990. *Discordant harmonies: A new ecology for the twenty-first century*. New York: Oxford University Press.

Van Buskirk, Josh, and Richard S. Ostfeld. 1995. Controlling Lyme disease by modifying the density and species composition of tick hosts. *Ecological Applications* 5(4): 1133-1140.

Diuk-Wasser, M. A. et al. 2006. Spatiotemporal patterns of host-seeking *Ixodes scapularis* nymphs (Acari: Ixodidae) in the United States. *Journal of Medical Entomology* 43(2): 166-176.

Diuk-Wasser, M. A. et al. 2010. Field and climate-based model for predicting the density of host-seeking nymphal *Ixodes scapularis*, and important of tick-borne disease agents in the eastern United States. *Global Ecology and Biogeography* 19: 504-514.

Duffy, David C. and Scott R. Campbell. 1994. Ambient air temperature as a predictor of activity of adult *Ixodes scapularis* (Acari: Ixodidae). *Journal of Medical Entomology* 31(1): 178-180.

Eisen, Rebecca J., Lars Eisen, and Charles B. Beard. 2016. County-scale distribution of *Ixodes scapularis* and *Ixodes pacificus* (Acari: Ixodidae) in the continental United States. *Journal of Medical Entomology*: 1:38.

Gleim, Elizabeth R. et al. 2014. The phenology of ticks and the effects of long-term prescribed burning on tick population dynamics in southwestern Georgia and northwestern Florida. *PLoS ONE* 9(11): 1-10.

Greenberg, Cathryn H., David L. Otis, and Thomas A. Waldrop. 2006. Response of white-footed mice (*Peromyscus leucopus*) to fire and fire surrogate fuel reduction treatments in a Southern Appalachian hardwood forest. *Forest Ecology and Management* 234: 355-362.

Guerra, Martin, et al. 2002. Predicting the risk of Lyme disease: Habitat suitability for *Ixodes scapularis* in the north central United States." *Emerging Infectious Diseases* 8(3): 289-297.

Humphrey, Parris T., Diane A. Caporale, and Dustin Brisson. 2010. Uncoordinated phylogeography of *Borrelia burgdorferi* and its tick vector, *Ixodes scapularis*. *Evolution* 64(9): 2653-2663.

Levi, Taal et al. 2012. Deer, predators, and the emergence of Lyme disease. *Proceedings of the National Academy of Sciences* 109(27): 10942-10947.

Levi, Taal, et al. 2016. Quantifying dilution and amplification in a community of hosts for tick-borne pathogens. *Ecological Applications* 26(2): 484-498.

Madhav, Nita K., et al. 2004. A dispersal model for the range expansion of blacklegged tick (Acari: Ixodidae). *Journal of Medical Entomology* 41(5): 842-852.

Morlando, Scott, Stephen J. Schmidt and Kathleen LoGiudice. 2012. Reduction in Lyme disease risk as an economic benefit of habitat restoration. *Restoration Ecology* 20(4): 498-504.

Ostfeld, Richard S., et al. 1995. Ecology of Lyme disease: habitat associations of ticks (*Ixodes scapularis*) in a rural landscape. *Ecological Applications* 5(2): 353-361.

Ostfeld, Richard S. et al. 2006. Climate, deer, rodents, and acorns as determinants of variation in lyme-disease risk. *PLOS Biology* 4(6): e145.

Pennsylvania Game Commission. 2016. *Barrens Habitat Management*. Report prepared for the State Lands Habitat Conservation Plan.

Pickett, Steward T., Jianguo Wu, and M. L. Cadenasso. 1999. Patch dynamics and the ecology of disturbed ground: A framework for synthesis. *Ecosystems of the World*: 707-722.

Prusinski, Melissa A. et al. 2006. Habitat structure associated with *Borrelia burgdorferi* prevalence in small mammals in New York State. *Environmental Entomology* 35(2): 308-319.

Rogers, Andrew J. 1955. The abundance of *Ixodes scapularis* Say as affected by burning. *The Florida Entomologist* 38(1): 17-20.

Ryan, Kevin C., Eric E. Knapp, and J. Morgan Varner. 2013. Prescribed fire in North American forests and woodlands: History, current practice, and challenges. *Frontiers in Ecology and the Environment* 11: 15-24.

Schulze, Terry L., Robert A. Jordan, and Robert W. Hung. 2001. Effects of selected meteorological factors on diurnal questing of *Ixodes scapularis* and *Amblyomma americanum* (Acari: Ixodidae). *Journal of Medical Entomology* 38(2): 318-324.

Schulze, Terry L. and Robert A. Jordan. 2005. Influence of meso- and microscale habitat structure on focal distribution of sympatric *Ixodes scapularis* and *Amblyomma americanum* (Acari: Ixodidae). *Journal of Medical Entomology* 42(3): 285-294.

Shumway, Durland L., Marc D. Abrams, and Charles M. Ruffner. 2001. A 400-year history of fire and oak recruitment in an old-growth oak forest in western Maryland, U.S.A. *Canadian Journal of Forest Research* 31: 1437-1443.

Stafford, Kirby C., Jeffrey S Ward, and Louis Magnarellli. 1998. Impact of controlled burns on the abundance of *Ixodes scapularis* (Acari: Ixodidae). *Journal of Medical Entomology* 35(4): 510-513.

Stafford III, Kirby C. 2004. *Tick management handbook: An integrated guide for homeowners, pest control operators and public health officials for the prevention of tick-associated diseases.* New Haven, USA: The Connecticut Agricultural Experiment Station.

Stephens, Scott L., and Lawrence W. Ruth. 2005. Federal forest-fire policy in the United States. *Ecological Applications* 15(2): 532-542.

Tiedemann, Arthur R, James O Klemmedson and Evelyn L Bull. 2000. Solution of forest health problems with prescribed fire: are forest productivity and wildlife at risk? *Forest Ecology and Management* 127: 1-18.

Vail, Stephen G., and Gary Smith. 2002. Vertical movement and posture of blacklegged tick (Acari: Ixodidae) nymphs as a function of temperature and relative humidity in laboratory experiments. *Journal of Medical Entomology* 39(6): 842-846.

Wilkinson, P. R. 1979. Ecological aspect of pest management of Ixodid ticks. *Recent Advances in Acarology* 2: 25-33.

Wilson, Mark L. 1998. Distribution and abundance of *Ixodes scapularis* (Acari: Ixodidae) in North America: Ecological processes and spatial analysis. *Journal of Medical Entomology* 35(4): 446-457.

Wormser, Gary P., et al. 2006. The clinical assessment, treatment, and prevention of Lyme disease, human granulocytic anaplasmosis, and babesiosis: Clinical practice guidelines by the Infectious Diseases Society of America. *Clinical Infectious Diseases* 43(9): 1089-1134.

Wu, Jianguo, and Orie L. Loucks. 1995. From balance of nature to hierarchical patch dynamics: A paradigm shift in ecology. *The Quarterly Review of Biology* 70(4): 439-46.