A GEOGRAPHICAL AND ENVIRONMENTAL ANALYSIS OF LYME DISEASE

by

SHARON LYNN TROTTER

(Under the direction of Dr. Vernon Meentemeyer)

ABSTRACT

This research demonstrates that August followed by July are the peak months for Lyme disease reports (1991 to 2000) across the 48 contiguous United States. Eight states have a secondary peak in December. For eleven states disease reports increased, two decreased and 34 had no trend (1991 to 2000). Greatest increases occurred in northeastern states, where the disease is already endemic. Climatic variables in the three months (April, May, June) prior to the summer peak have strong relationships with disease reports/rates. Ninety percent of all cases occur in counties with an average temperature in April, May, June between 10.99 and 17.92°C, soil moisture surplus values of 3.43 to 11.00 centimeters, and precipitation values of 23.57 to 33.45 centimeters. The disease system appears to be constrained more by moisture than temperature. The predictive "climatic envelope" model was used to produce a risk map for Lyme disease.

INDEX WORDS: Lyme disease, Geography, Climate, Landuse, Seasonality, Weather

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SHARON LYNN TROTTER

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SHARON LYNN TROTTER

Approved:

Major Professor: Vernon Meentemeyer

Committee: Andrew Grundstein
Steven Holloway

Electronic Version Approved:

Gordhan L. Patel
Dean of the Graduate School
The University of Georgia
August 2002

DEDICATION

This thesis is dedicated to John Howard Harmon III. It is your strength and determination in accomplishing your own goals that has been such an inspiration for me. Additionally, your ability to listen for hours on end is what keeps me sane. You continue to amaze me day after day and I can never express how proud I am of you for ‘standing’ up to your fate. Your friendship means the world to me.

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CHAPTER 1. INTRODUCTION

A formal definition of Lyme disease is, "an acute inflammatory disease characterized by skin changes, joint inflammation, and flu like symptoms, caused by the bacterium *B. burgdorferi* transmitted by the bite of a deer tick" (WebMD Medical Library 22 March 2001). Some of the symptoms and signs of Lyme disease are a circular, bull's–eye rash, fatigue, chills and fever, headache, muscle and joint pain, and swollen lymph nodes. When left untreated, more serious symptoms and signs may occur months or years after the initial tick bite including arthritis (usually in the knees), nervous system abnormalities, (i.e., numbness, paralysis of the facial muscles), meningitis, and irregular heartbeat (less frequently). The most common and usually the first symptom is a rash, although some people exhibit only arthritis or nervous system problems (CDC 13 May 2001).

The disease has affected greater than 100,000 people over the past ten years with 1999 reports showing that 92 percent of the reported cases occur in the Northeast and Mid–Atlantic states (Massachusetts to Maryland) and the Upper Midwest (Minnesota and Wisconsin) (CDC 22 March 2001). In addition, there is a smaller endemic focus (California and Oregon) located in the far western U.S. (Figure 1) (CDC 22 March 2001). Figure 1 is based on data used for this study for the years 1994 to 1999 and is similar to previous maps produced by the CDC, although the time periods differ. Most infections tend to occur during the summer months, in rural and suburban areas when the tick is most active (CDC 22 March 2001). In the northeastern and north–central U.S., May through August have the highest reports with June and July generally being accepted as the peak months (WebMD Medical Library 22 March 2001, Gubler et al. 2001). Western noncoastal areas tend to have high reports in the months of January through May, and western coastal areas have a high percentage of reports between November and April (WebMD Medical Library 22 March 2001).

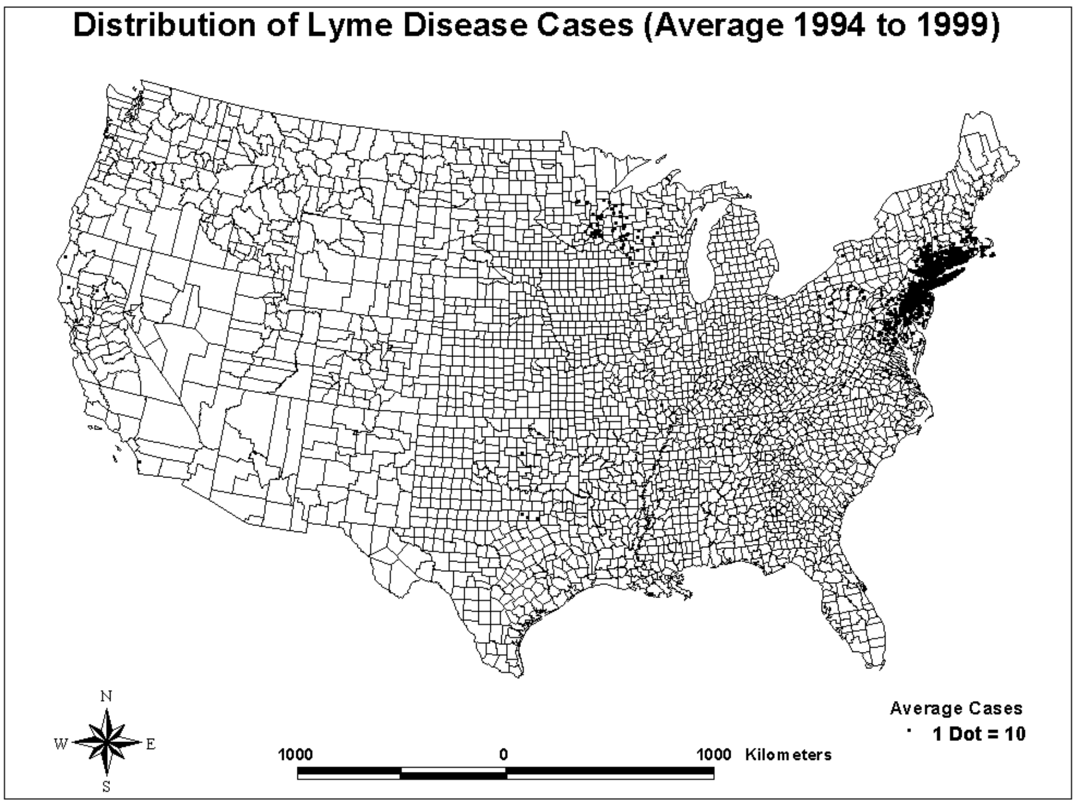

Figure 1: Spatial distribution of Lyme disease cases by county across the U.S. (based on an average value from 1994 to 1999).

Lyme disease, currently the most common arthropod–borne disease in the United States, was first discovered in 1977 in Lyme, Connecticut (Orloski et al. 2000). An unusually large number of children were displaying signs of arthritis and eventually the unidentified phenomenon was called Lyme disease (WebMD Medical Library 22 March

2001). This disease is caused by a spiral–shaped bacterium, *Borrelia burgdorferi* (*B. burgdorferi*), which belongs to the family *Spirochetes* (CDC 22 March 2001). Lyme disease is spread by ticks of the genus *Ixodes* that are infected with the bacterium. Furthermore, in northeastern, north–central, and southern United States, the deer or black–legged tick (*Ixodes scapularis* or formerly known as *Ixodes dammini*, Oliver et al. 1993) is responsible for the transmission of the disease, and on the Pacific coast the western black–legged tick (*Ixodes pacificus*) is responsible for transmission (Shapiro and Gerber 2000).

The environment within a geographic area and the stage of the tick's life cycle are important in determining the proportion of infected ticks. In regions of the northeastern U.S., approximately 25 percent of *Ixodes scapularis* (*I. scapularis*) are infected with the bacterium in the nymphal stage and approximately 50 percent in the adult stage (Dennis et al. 1998). Whereas, in the southern U.S, *I. scapularis* normally feeds on lizards, which are "reservoir incompetent" for the bacterium*, B. borgdorferi*; therefore, only one to three percent of the ticks are ever infected with the bacterium (Dennis et al. 1998). The *Ixodes* ticks are extremely small ranging from a diameter smaller than a pinhead to only slightly larger. They search for their host animals (i.e., white–tailed deer, white–footed mouse) from grasses and shrubs, and feed by inserting their mouthparts into the skin of the animal (CDC 22 March 2001).

1.1 Rationale

Lyme disease has been termed a "resurging" disease and is distributed globally. It is suspected that the resurgence is caused not only by the establishment of the vector but also climate, immunity status, density of human populations, and presence of a suitable reservoir host (Gratz 1999). Furthermore, Gubler et al. (2001) states that arthropod–borne disease vectors, their hosts, and the transmission cycle all have links to the climate of the region in which it occurs. Climatic factors such as temperature, rainfall, and humidity are important in the presence or absence of the arthropod–borne diseases because variations in these entities may increase or decrease the longevity of the vector's life span (Gubler et al. 2001). Consequently, a longer life span permits a longer period of potential contacts. Loper (1999) states that vector–borne diseases are susceptible to weather characteristics such as temperature and rainfall because they may affect the reproductive processes of both the pathogen and vector. Additionally, the vector (tick) transmitting the disease may be affected by climate in their horizontal and vertical distribution, life cycle, seasonal activity, population dynamics, and the behavior of both tick populations and individuals (Daniel and Dusbabek 1994).

The tick's water balance and its relationship to the atmospheric humidity may be of importance to the survival of ticks (Knulle and Rudolph 1982). During a tick's non-feeding period, the atmosphere can dehydrate the tick; therefore, the tick must attempt to maintain its water balance. The tick can instead gain the needed water from the atmosphere, which is generally favorable in their sheltered microclimates in forest litter, when high relative humidity and moderate temperatures prevail. The water balance of the tick is most critical when the tick leaves its favored microclimate and ventures out into unprotected soil surfaces or up on vegetation to seek their host. In general, most tick species have a threshold atmospheric humidity at which the tick will continually lose water, approximately 75 to 94 percent (Knulle and Rudolph 1982).

Past research has determined that there should indeed be relationships between climatic factors and vector–borne diseases; except in very general terms there have been few studies of climatic relationships with Lyme disease, the U.S.'s leading vector–borne disease (Lane 1994). That this disease expresses seasonality has often been reported, which suggests that weather and climatic variables should enter into the epidemiology of Lyme disease. Therefore, this proposed research will first investigate the geography of the seasonality of Lyme disease, and thereby begin a search of specific geographic/climatic variables that have an impact on its occurrence and infection rate across the contiguous U.S.

1.2 Specific Objectives

The goal of this study can be broken down into the following detailed objectives. Based on past research (i.e., WebMD Medical Library 22 March 2001, Gubler et al. 2001), the peak months for reports of Lyme disease are reported to occur in June and July for the northeastern United States. Furthermore, the disease normally occurs between January and May in non–coastal western states and between November and April for the midwestern United States (WebMD Medical Library 22 March 2001). Previous literature has not reported a specific peak month or months of Lyme disease occurrences for each of the 48 contiguous states; therefore, the first objective will be to examine the seasonality of Lyme disease report data by state for the years 1991 through 2000 in order to create a map of the U.S. of the peak month(s) by state.

Secondly, the year–to–year variability for each state will be analyzed to identify the trend (increasing or decreasing in frequency) of this disease across the country. It is also expected that these first two objectives will provide "clues" to a link between climate (and other factors) and Lyme disease.

A third objective will analyze the relationship between population/population density of a county and the number of Lyme disease reports. If people are to contract the disease they must come into contact with the tick. Do suburban and rural areas have the highest rates as suggested in the literature?

A fourth objective will be to investigate the climatic parameters that are linked closely with the high incidence of Lyme disease reports across the contiguous U.S. Therefore, variables such as mean monthly and yearly temperature, mean monthly and yearly precipitation, and mean monthly and yearly soil moisture deficit and surplus values will be descriptively and statistically related with the Lyme disease reports in order to discover whether there is a most suitable and desirable climatic habitat in which Lyme disease tends to thrive. Is there a core climate zone for the disease and its vectors?

An attempt will be made to identify the "ingredients" necessary to support the host–vector system for Lyme disease. A susceptible human population must be present and able to contact the infested tick. It is likely that the counties with the highest report rates have the animal hosts, the correct supporting ecosystem, and correct climatic limits of heat and moisture. This will involve analyzing the landuse characteristics of the counties with high and low rates of Lyme disease reports to determine whether it has a control on the spatial distribution of Lyme disease. Lastly, a climate model will be created to outline geographic areas with a suitable climate to support the disease, which under the right circumstances may become endemic with Lyme disease.

CHAPTER 2. BACKGROUND

2.1 Introduction

Only a small number of studies have been conducted to examine the effects of certain meteorological variables on the activity, density, and survival of the deer tick, *I. scapularis,* including Duffy and Campbell 1994, Jones and Kitron 2000, Lindsay et al. 1995, Vail and Smith 1998, Stafford 1994, VanDyk et al. 1996, Schulze et al. 2001. The macroclimatic relationships may be beneficial in understanding the gross spatial and temporal distribution and limitations of Lyme disease across the U.S.

At an entirely different scale, there has been research on the effect that varying temperature has on the actual bacterium, *B. burgdorferi* (Shih et al. 1995). Furthermore, reservoirs for the bacterium have been investigated with efforts to understand the range of animals capable of carrying this tick–infested disease and the competence that these animals have in maintaining the disease bacterium, *B. burgdorferi* (Mather and Ginsberg 1994, Keirans et al. 1996, Gray et al. 1992, Gray et al. 1998).

This research will focus on this disease from a macroscale perspective. Thus, Lyme disease will be descriptively analyzed for the entire contiguous U.S. Also the climatic factors affecting the disease will also be examined on a macroscale. Therefore, when researching the spatial distribution of the disease, the endemic areas of the disease will be used to determine any control that environment has on Lyme disease outbreaks.

2.2 *I. scapularis and I. pacificus* Ticks

The life cycle of the deer tick is significant to the transmission of Lyme disease to the host and consequently to humans because of its seasonality (Keirans et al. 1996). Environmental conditions may affect the timing of development of the tick, thereby, increasing the importance of understanding its cycle (Padgett and Lane 2001). Furthermore, Bertrand and Wilson (1996) state that the microclimatic characteristics of the tick's habitat are important in both the development and survival of ticks.

2.2.1 I. scapularis and I. pacificus Stages and Life Cycle

There are three stages to the life cycle of the *I. scapularis* including larvae, nymph, and adult (Anderson and Magnarelli 1993). The first (larvae) stage of the cycle does not carry the bacterium, although the second and third stages (nymph and adult) can occur in both infected and uninfected forms (Van Buskirk 1995). The tick can be infected at any stage of its life cycle by feeding and becoming engorged on a host that is a competent reservoir for the bacterium, *B. burgdorferi* (Shapiro and Gerber 2000). Competent reservoir hosts are animals that are capable of acquiring the infectious organisms from the tick, and subsequently maintaining and donating them to other ticks (Sonenshine 1994). Consequently, because of its small size and ability to feed quicker than mature ticks, the nymphal stage of the *I. scapularis* is most likely to transmit the infection to humans entering the tick's habitat during the spring and summer (Shapiro and Gerber 2000). Furthermore, although adult ticks can transmit the disease they are less likely to do so because of their larger size and their peak activity, which occurs in winter when human outdoor activity is limited (CDC 02 March 2001).

Yuval and Spielman (1990) describe the life cycle of the *I. scapularis* (Figure 2) as extending greater than two years for black–legged ticks occupying the northern U.S. with the nymphal stage of the tick appearing in May and June and feeding at this time on its host. Additionally, Yuval and Spielman (1990) report that adult ticks feed between the months of September and May, whereas, larvae feed in the late summer months where they may become infected if feeding occurs from a nymphal–infected host. The black–legged tick populating the southern U.S. may exhibit a shorter life cycle of at least one year, therefore, requiring both nymphs and larvae to feed from January to September (Oliver 1996).

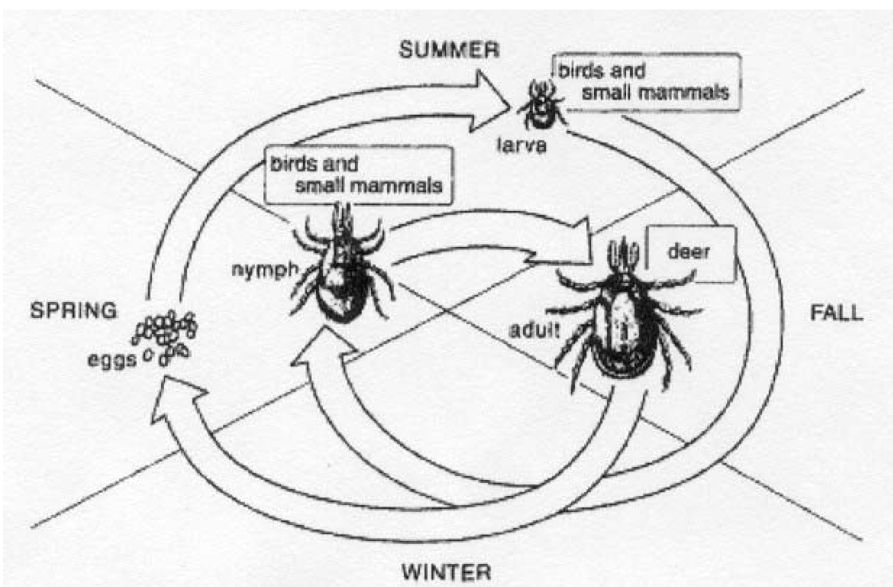

Figure 2: Life Cycle of the tick, *I. scapularis* (from Van Buskirk and Ostfeld 1995).

Similarly to the *I. scapularis*, the *I. pacificus* is characterized by three stages (Figure 3) in its life cycle including larvae, nymph, and adult (Padgett and Lane 2001). Padgett and Lane (2001) report evidence that this tick requires a minimum of three years to complete its life cycle. The larvae feed primarily in March and April and remain inactive until the following late winter months where they reemerge as nymphs and begin host–seeking. Nymphs that find and feed on a host ultimately evolve into adults in late summer and normally survive at least until the next summer, although summer drought conditions may terminate a large number, especially if unfed (Padgett and Lane 2001).

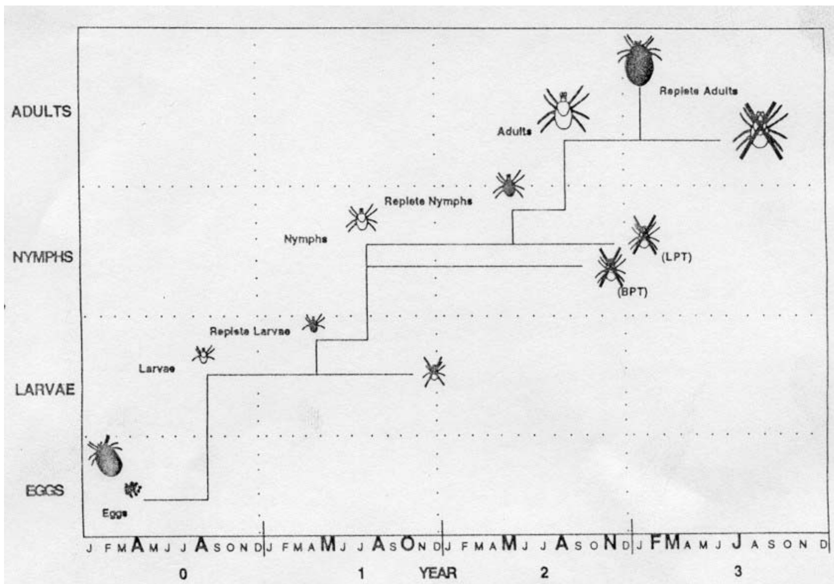

Figure 3: Life Cycle of the tick, *I. pacificus* (from Padgett and Lane 2001).

2.2.2 I. scapularis and I. pacificus Habitat

Dennis et al. (1998) investigated the distribution of both the black–legged tick and the western black–legged tick (Figure 3) (*I. scapularis* and *I. pacificus*, respectively) and report that the black–legged tick has established populations (i.e., at least six ticks or two life stages reported) in 396 counties in 32 states, and another 556 counties have reported populations of the black–legged tick. These counties stretch from northern Maine down to the Gulf coast states with populations also in the states of Michigan, Wisconsin, Minnesota, and Iowa. Dennis et al. (1998) found that the western black–legged tick is established in 90 counties in five states in the west with 56 of the counties located in California and the remainder in Washington, Portland, Arizona, and Utah. Additionally, 16 other counties in the west have reported populations of the western black–legged tick. These ticks mostly limit themselves to deciduous woodlands where large animals (i.e., deer) are abundant, although they can be found in coniferous forest as long as the leaf litter is sufficient and the climate is moist. Gray (1998) reveals that the questing and developmental stages need a relative humidity in their microclimate of no less than 80 percent throughout the year.

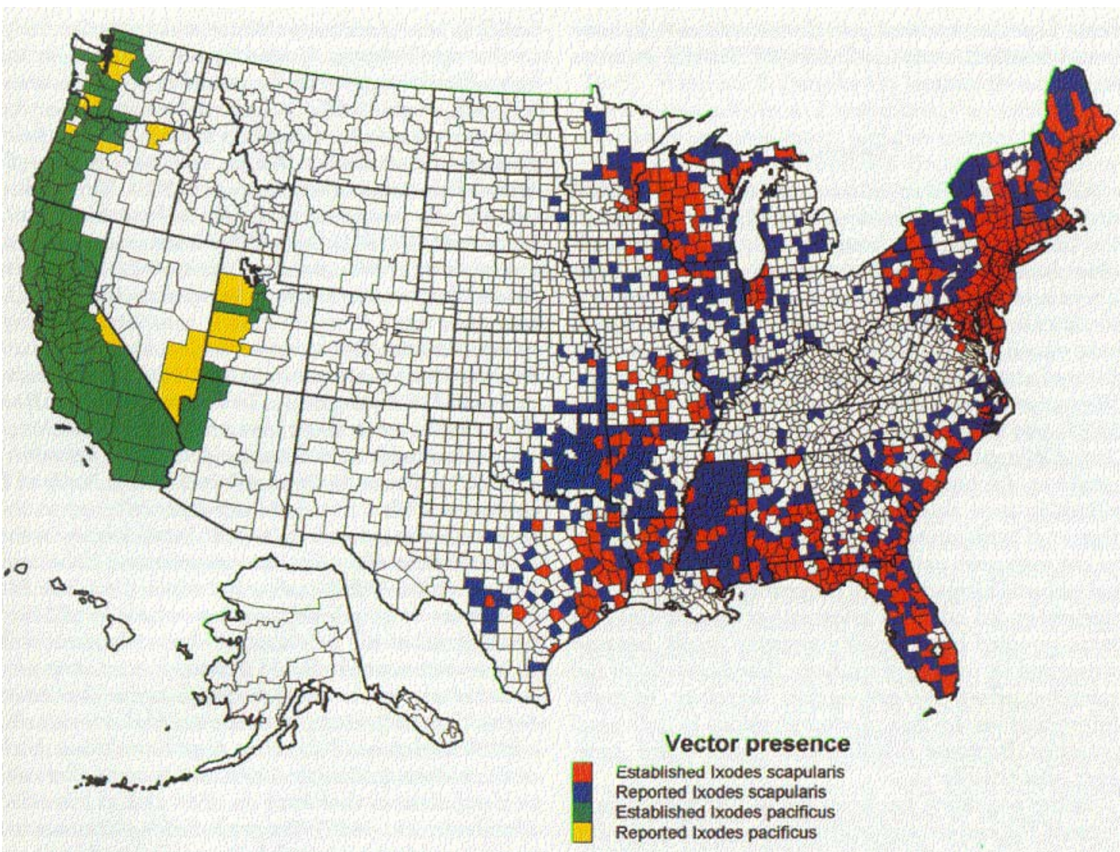

Figure 4: Spatial distribution of *I. scapularis* and *I. pacificus* in the U.S. (from the CDC 2001, http://www.cdc.gov/ncidod/dvbid/lyme/tickmap.htm).

A study into the spatial dynamics of *I. scapularis* in a semirural landscape in southeastern New York show that all three stages of the tick were more prevalent in forested areas as opposed to nonforested habitats over a three year period (Ostfeld et al. 1996). Additionally, a study of 400 residential properties in a highly endemic area, Westchester County, NY, reveals that the presence of nymphs on a residential property is negatively correlated to the percent of lawn and positively correlated by the percent of woodland (Frank et al. 1998). Although, Nicholson and Mather (1996) suggest that there are possibly other factors such as cooler winters, drier summers, forest structure, and/or soil type that may regulate tick abundance, infection rate, entomological risk, or human risk, besides that of the amount forest in an area. Bertrand and Wilson (1996) also conclude that the longevity of unfed adult *I. scapularis* survival was longer in forested and edge habitats as opposed to open areas. Open–field conditions exhibit higher ground air temperature and soil temperature and lower relative humidity; therefore, suggesting that survival time of unfed adults is increased with higher relative humidity values and lower temperatures (Bertrand and Wilson 1996).

2.3 Tick Hosts

2.3.1 Reproductive and Reservoir Hosts

Some research has included the range of mammals that act as hosts for the deer tick (Mather and Ginsberg 1994, Keirans et al. 1996, Gray et al. 1992, Gray et al. 1998). These hosts are divided into two groups; reproductive hosts which provide a meal for the ticks furthering their life stage, and reservoir hosts which advance both tick populations and infection rates (Mather and Ginsberg 1994). Some hosts commonly sought by the adult black–legged tick are the white–tailed deer, which is one of the most important hosts, as well as cattle and dogs (Keirans et al. 1996). Gray et al. (1998) explains that these large hosts are important in maintenance of tick populations because they are necessary for adult tick reproduction. White–footed mice, skunks, and certain reptiles (i.e., lizards) are important hosts for the two immature stages of the black–legged tick (larvae and nymph) (Keirans et al. 1996). Furthermore, Gray et al. (1992) states that the smaller mammal hosts are important for the infection's survival and the infection of the ticks.

2.3.2 The Host's Habitat and Distribution Range

The habitat range of the white–tailed deer and white–footed mouse, two of the more important and prominent reservoir hosts for the deer tick (Anderson and Magnarelli 1980), is an extremely important element in the transmission of Lyme disease to humans simply because the absence of the reservoir host will eliminate any possibility of the bacterium being maintained in that region. The dominant reservoir host for the immature black–legged ticks, the white–footed mouse, is primarily an inhabitant of wooded and brushy areas, although it has been found to dwell in more open ground (CDC 13 May 2002). The mouse is distributed throughout southern New England and the Mid–Atlantic as well as throughout the southern, midwestern and western states of the U.S. (CDC 13 May 2002). Furthermore, the dominate host for the adult tick, the white–tailed deer, makes its habitat in open woodland, cutover forests, zones between woodlots and urban areas, and in farming country; interestingly it does not thrive or normally even inhabit mature forested areas (Encyclopedia Britannica 2002). This deer ranges from southern Canada to South America except for the extreme the far western and southeastern U.S. (Quality Deer Management Association 15 May 2002).

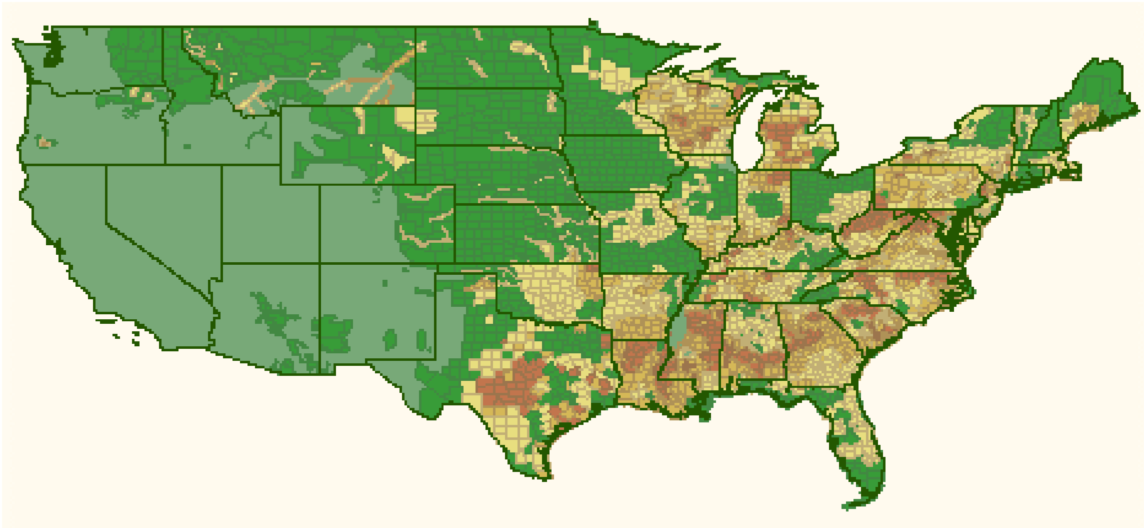

Figure 5: Population density of the white–tailed deer in the U.S., dark brown represents highest density with no reports of populations represented by light green (from www.qdma.com 2002, Quality Deer Management Association, produced by I–Map Data System, LLC).

2.4 The Potential Importance of Climate for Lyme Disease

According to Keirans et al. (1996) Lyme disease has become more prevalent in the last ten years and is geographically spreading across the U. S. The disease can be limited by unfavorable habitat conditions for both the tick and host including environmental elements that may reduce ambient humidity (i.e., desert conditions) (Keirans et al. 1996). In addition, areas of heavy agricultural practice also limit the geographical spread of Lyme disease across the U.S. (Keirans et al. 1996). Accordingly, the microclimate (a combination of the region's biotope and climatic conditions, local soil and vegetation characteristics) of a region is one of the aspects that limits the survival and influences the distribution of the black–legged tick in North America (Wilson 1998). The influence of climatic variables on the tick is an important relationship because the strong correlation found between Lyme disease and local density of *B. burgdorferi-*

infected nymphal deer ticks in the northeastern and mid–Atlantic U.S. (Nicholson and Mather 1996). Therefore, understanding the climatic impact on the vector of the disease should help further investigation into spatial and temporal distribution of Lyme disease.

2.5 The Role of Temperature in Bacterium Survival

Shih et al. (1995) studied the effect of temperatures ranging from 27°C to 37°C throughout the duration of nymphal stage of infected ticks in order to understand the survival rate of spirochetal infection. They concluded that Lyme disease spirochetes do not survive in an environment with temperatures greater than 27°C.

2.6 The Role of Humidity, Precipitation, and Temperature in Tick Survival

2.6.1 Precipitation, Humidity and Tick Survival

Examining the effect of relative humidity during the summer months on the survival of immature *I. scapularis*, Stafford (1994) found that larvae and nymphs, in general, prefer a higher relative humidity (i.e., 93 or 100 percent) to a lower relative humidity (i.e., 85 or 75 percent). Consequently, nymphs are able to survive for longer stretches and at lower relative humidity than the larvae (Stafford 1994). The density and distribution of leaf litter in the tick's habitat is an important factor in their survival because it supplies the tick with a more humid resting place during dryer, hotter periods (Lindsay et al. 1999). Consequently, removal of the leaf litter found in the tick's habitat has been found to significantly reduce the population of the active nymphal black–legged tick in the months of March and June by 72.7 to 100 percent (Schulze et al 1995). Additionally, populations of *I. scapularis* can be reduced when drought conditions have been experienced in the year (Jones and Kitron 2000). Jones and Kitron (2000) also conclude that rainfall is a key element in regulating tick populations.

2.6.2 Temperature and Tick Survival

Duffy and Campbell (1994) performed an experiment to discover whether there is a minimum temperature in which the adult *I. scapularis* could remain active. They report that 4°C is the minimum temperature, which suggests that ticks can still be active in winter in many regions even though that is not the peak season. Although, Schulze et al. (2001) found that adult *I. scapularis* could quest and remain active in temperatures as low as -0.6°C, which is lower than previously reported. Furthermore, because the life cycle of the *I. scapularis* requires that the tick overwinter (i.e., do not host–seek) in all of its stages, the importance of temperature becomes apparent in the survival of the tick and the bacterium transmission (VanDyk et al. 1996). The un–engorged infected nymph stage being the most important overwintering stage because it is needed to transmit the bacterium to the reservoir host in the spring (VanDyk et al. 1996). VanDyk et al. (1996) found that more un–engorged nymphal *I. scapularis* survive severe winters (-18°C) when compared to the other stages of the tick (both in the engorged and un–engorged states).

2.6.3 Temperature, Humidity and Tick Survival

The temperature variation can also affect mean nymph density of an area by decreasing the mean nymph density/100m^2 as the regions temperature increases (Vail and Smith 1998). Vail and Smith (1998) conclude that temperature and humidity significantly affect residual density/100m^2 based on results of their study site in Morristown, New Jersey. They found that residual density/100m^2 decreases as temperature values increase and increases when relative humidity values increase. Furthermore, this research showed that temperature and humidity explained 34 and 44 percent of the variability in residual density/100m^2 respectively (Vail and Smith 1998). In addition, adult *I. scapularis* tend to quest at earlier and later times of the day when temperatures are lower and relative humidity higher, although they can be found questing at other times of the day (Schulze et al. 2001). Taking into account both temperature and humidity variables, a study in south central and northwestern Connecticut found that vapor pressure deficit, was negatively related to the average daily survival rates of ticks, therefore, the greater the "drying" power of the atmosphere, the more survival rates began to drop (Bertrand and Wilson 1996).

2.7 Tick Dynamics

Lastly, there have been specific states in the U.S. that have been researched (Table 1) with respect to their tick population, distribution, activity, and survival (French et al. 1992, Kollars et al. 1999, Schulze and Jordan 1996, Lord 1995, Daniels et al. 1989, McEnroe 1977, Daniels et al. 1996, Goddard 1992, Lyon et al. 1996, Stafford and Magnarelli 1993). These region specific studies tend to have conclusions regarding the black–legged tick that are in general agreement with conclusions made for the entire contiguous U.S. For areas in the Northeast, there is high seasonal and yearly variability in tick populations; much of this variability can be related to the timing of reproduction and other population dynamics across habitats (Lord 1995, McEnroe 1977). Furthermore, in the Northeast it is found that the tick dominates woodlands and transition zones between lawn and woodlands (Stafford and Magnarelli 1993). In the Northeast, adult ticks have been found to survive the winter, but prefer areas of warmer winter and fall temperatures (Daniels et al. 1989, 1996). In Mississippi, adult tick activity peaks in February and in Missouri the adult peak activity is in November with a lesser peak in February with their nymphs peaking in May and June, which resembles the findings for the northeastern and north–central regions (Goddard 1992, Kollars et al. 1999). Additionally, Missouri's dominant host for the tick was indeed the deer, lizards, and skunks, which also keeps in agreement with the findings for the rest of the U.S. (Kollars et al. 1999).

Table 1: Literature on tick population, distribution, activity, and survival

State	Arthur / Date	Description of Findings
Wisconsin	French et al. 1992	During 1980's *I. dammini's* range expanded in the N–S and increased its population density in colonized areas.
Missouri	Kollars et al. 1999	Activity of *I. scapularis*; Adult peak in Nov. and lesser in Feb., larval in July, and nymph in May and June. Important hosts: Adults–large animals (deer) and nymphs/larvae-small animals (lizard, skink).
New Jersey	Schulze and Jordan 1996	High seasonal and year–to–year (three years) variability in populations of adult *I. scapularis*, although variability lower in spring.
New Jersey	Lord 1995	Different habitats (deciduous vs. non–deciduous) display different population dynamics of nymphal *I. scapularis*.
New York	Daniels et al. 1989	Adult *I. dammini* can successfully overwinter and resume host–seeking in the spring.
New York	Daniels et al. 1996	Range of *I.scapularis* is restricted to the coastal areas where fall and winter temperatures are higher than inland temperatures. Minor shifts around the mean cause population crashes and explosions.
Massachusetts	McEnroe 1977	Timing of reproduction and larval activity varies from one region to the next. Temperatures are not a good indicator of reproductive success.
Mississippi	Goddard 1992	Adult *I. scaplaris* questing activity peaked in early Feb. Ticks were most often collected at ≈ 20°C and were clustered and not evenly distributed in the site.
Massachusetts	Lyon et al. 1996	Estimated the number of *I. scapularis* feeding on white–footed nice in 1991.
Connecticut	Stafford and Magnarelli 1993	*I. scapularis* nymphs and larvae tended to be found in woodlands, and adults were found in lawns or lawn to forest zones (1989–1991). Risk of exposure to infected nymphs varies with landscape, residence, and temporally.

2.8 Summary

This review has shown that the research into the relationship of climate and Lyme disease is limited, although there is substantially more research describing the evidence of links between vector–borne diseases and climate in general. Past research has shown the potential importance of climate, both macro and micro scale, in the transmission process of Lyme disease by studying the effect of different climatic and meteorological factors on *I. scapularis* and *I. pacificus* survival as well as the survival of the bacterium, *B. burgdorferi.* The relationship between climate and the vector is of utmost importance in determining the impact of climatic variables on the spatial distribution of Lyme disease across the country. Furthermore, the seasonal distribution has been discussed in simple and broad regional terms in the literature; this research strives to report a more thorough and concise seasonal pattern by showing the peak seasonal distribution and yearly variability of the disease on a state basis. Moreover, this research will initiate the investigation to unveil any relationship that climate, human population, and landuse variables have with Lyme disease reports on the county geographic level. Lastly, a climate envelope model will be created to show counties in the U.S. that are within the climatic limits of energy and moisture to support high rates of Lyme disease. Therefore, depending on the county's host, tick, and human populations these counties are prime suspects to become endemic with Lyme disease.

CHAPTER 3. DATA AND METHODOLOGY

3.1 Introduction

Lyme disease in the U.S. has been researched and documented and although the CDC has mapped the infection reports by county, no thorough analysis of the basic geographical pattern has been performed. This study starts by using Lyme disease statistics to describe the seasonal/temporal distribution and the year–to–year trend of the disease across the U.S. by state. There are two main areas in the U.S., where this disease has reached epidemic proportions, which indicates that it is geographically restricted by environmental mechanisms. Furthermore, this research will examine this geographic distribution by focusing on how macroscale climate factors and county population/population density estimates may enter into the occurrence of Lyme disease reports by county. Since the transmission of the disease is so complex in nature and includes many elements, climate is obviously understood to not be the direct cause of this disease, but instead it supplies the required levels of heat and moisture necessary to support its occurrence. The land–use of the county may be one of the other factors contributing to its spatial distribution; therefore, a brief investigation into the landuse of selected counties will also be done. A final objective will be the creation of a "climatic envelope" model for the disease. This model will in fact be a model of disease risk. To fulfill the aforementioned detailed objectives of this research a descriptive analyses will be done.

3.1.1 Assumptions of Research

To investigate climatic influence and correlations with Lyme disease, this research is based upon observations that Lyme disease corresponds highly with local tick density (Nicholson and Mather 1996). Unfortunately, no data are available for tick density or the tick's likelihood of carrying the bacterium and only fragmentary data exists for the host–vector system of the tick. Therefore, to reveal possible relationships with macroclimatic variables, this research will use Lyme disease reports as an outcome, or a surrogate, to tick density data and human–tick contacts. It is assumed that the county of Lyme disease report is the county in which the person acquired the bacterium from the tick. This assumption is supported by findings of Falco and Fish (1988) for an isolated county in the Lyme disease endemic area, Westchester County, NY. They found that cases in this county can be associated with the local presence of *I. dammini* in the well-maintained yards/lawns of the residence of the Lyme disease patient, and they suggest that cases in this county and possibly other endemic areas may have been acquired from home activities in the yard (Falco and Fish 1988). Moreover, the presence of the white-footed mouse was also associated within the vicinity of the residence (Falco and Fish 1988).

This study uses Lyme disease reports as a surrogate to tick density data and human–tick contacts. A period of about one to four weeks is needed between the time that the tick becomes attached to a person and the disease is recognized (WebMD Diseases and Conditions 14 June 2002). Despite the extreme variability of the seasonality of Lyme disease, the overall peak season of June, July, and August will be used to investigate any climatic controls entering into the disease since this is the time when the disease peaks in the two main endemic areas of the Northeast and Upper Midwest. Therefore, this research assumes that the weather/climate of the preceding months (i.e., January, February, March, etc.,) of the same year are likely important controls on the tick's population dynamics and survival. The aforementioned research by VanDyk et al. (1996) describes the cold hardiness of the un–engorged nymph, which is mostly credited for transmission of bacterium to humans (Shapiro and Gerber 2000). This research is based on the observation that the cold months of a year are important for tick survival and their resulting population density in the following active spring and summer months. The three–month period in the warm season directly preceding the general peak occurrence of Lyme disease (i.e., July and August) is also important because the nymphal stage is most active in the late spring and early summer (Yuval and Spielman 1990). Therefore, the climate during late winter and spring/summer may determine the population of nymphal ticks that should spread the disease in the summer. Thus, the average or total value for the three–month period of January, February, and March (JFM) and April, May, and June (AMJ) will be used to quantify the range of precipitation, temperature, soil moisture surplus, and soil moisture deficit values that corresponds with high reports of Lyme disease. Ultimately, through the analysis of each lagged time period, it may be possible to demonstrate a "most favorable" macroclimate.

3.2 Data

3.2.1 Lyme Disease and Census Data

The Lyme disease report data were collected from the Centers for Disease Control and Prevention (CDC) via Ned Hayes, Chief of the Epidemiology Section within the Division of Vector–borne Infectious Diseases, and Ruth Ann Jajosky from the

Epidemiology Program Office. The Lyme disease data includes raw county Lyme disease reports by year for the time period 1994 through 1999 and also state Lyme disease reports by month for the time period of 1991 through 2000. Counties with less than five reports for a year were specified with a star in the original dataset; therefore, under direction of Dr. Ned Hayes these "star" value reports were replaced with an average value of 2.5 reports. Unfortunately, the optimal data required for this project (i.e., Lyme disease reports by county by month) are not publicly available.

The county population data used to normalize the Lyme disease data by population comes from the 1999 U.S. Census Bureau website (www.census.gov). Accordingly, county population density data were calculated from the aforementioned 1999 population data and U.S. county area (given in square mile) values which were downloaded from ESRI *ArcView GIS* Version 3.0.

3.2.2 Climate Data

Due to previous research showing that many vector–borne diseases, including Lyme disease, are related to temperature and environmental moisture (Daniel and Dusbabek 1994, Gratz 1999, Gubler et al 2001, Keirans et al 1996, Knulle and Rudolph 1982, Loper 1999, and Wilson 1998), the climatic variables selected include: average monthly mean temperature (°C); average monthly total precipitation (centimeters); and monthly total surplus and deficit soil moisture values (centimeters). The temperature, precipitation, and soil moisture values are given by state climate division for the years 1994 through 1999. The precipitation and temperature data were obtained from the National Climatic Data Center (NCDC). Furthermore, soil moisture data were generated using a program based on the Thornthwaite–Mather water balance method that used monthly total precipitation and average monthly temperature from climate division data, available from the NCDC. It must be noted, that the program was designed to only output soil moisture surplus and deficit values.

Climate division climate and soil moisture variables were chosen because this research is investigating a macroclimatic influence on the spatial distribution of Lyme disease and not a microclimatic influence, therefore, one geographic level above the county Lyme disease data was selected (i.e., climate division). Climate divisions are based on the climate of a given state and divided into divisions based on like climatic regimes of regions in that state. Each of the 48 contiguous states is divided into a minimum of four to a maximum of ten climate divisions. The climate divisions were matched with the county Lyme disease data. Fortunately, the climate divisions for each state on the most part coincide with the county boundaries of the state, resulting in a very good county–climate division match. The boundaries do not coincide perfectly for every state, so the county is matched to the climate division that greater than half of its area is located.

3.3 Descriptive Analysis Methodology

For the descriptive analysis, first the mean monthly Lyme disease reports (1991-2000) are graphed for each state using *SPSS* to reveal the peak month or months for the disease across the U.S. (Figure 6). These results are compiled and mapped in *ArcView* to see the seasonal and temporal distribution of Lyme disease across the U.S.

Next, to assess each state's individual disease trend, the annual value of the disease is graphed using *SPSS* and a regression line is fit to the annual values (Figure 7). The slope of the regression line is used to determine the trend of the disease. Statistically significant slopes are those reported as significant at a 95 percent confidence interval using a two–tailed test. States with less than ten cases for all years of the ten–year period were assumed to be “statistically unstable”. Trends by state were compiled and mapped in *ArcView* to show the trend variability across the U.S.

In addition, the yearly county Lyme disease reports are plotted against population and population density using *SPSS* to assess the nature of the relationship (i.e., linear, non–linear) between the population of a county and the reports of Lyme disease in that county. The Lyme disease reports will then be adjusted by both population and population density and mapped in *ArcView* to see any change in the character of the distribution of the disease when the cases are adjusted for any population biases.

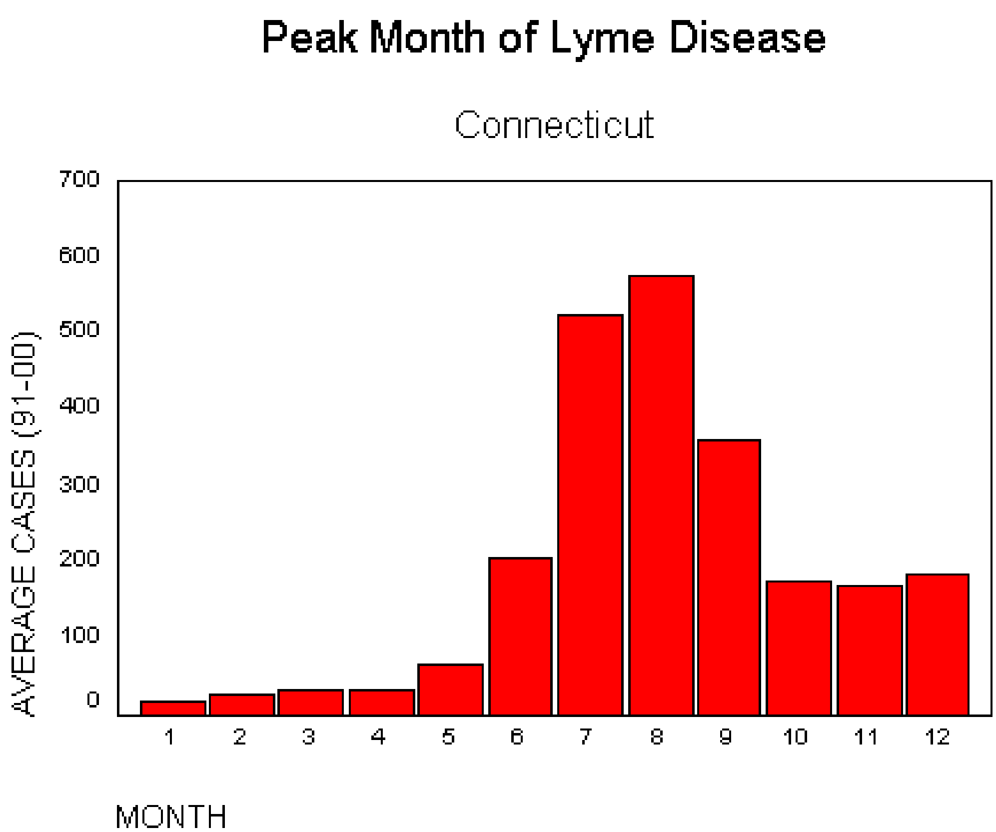

Figure 6: Example of chart of peak month (Connecticut) based on average cases for the period 1991 to 2000.

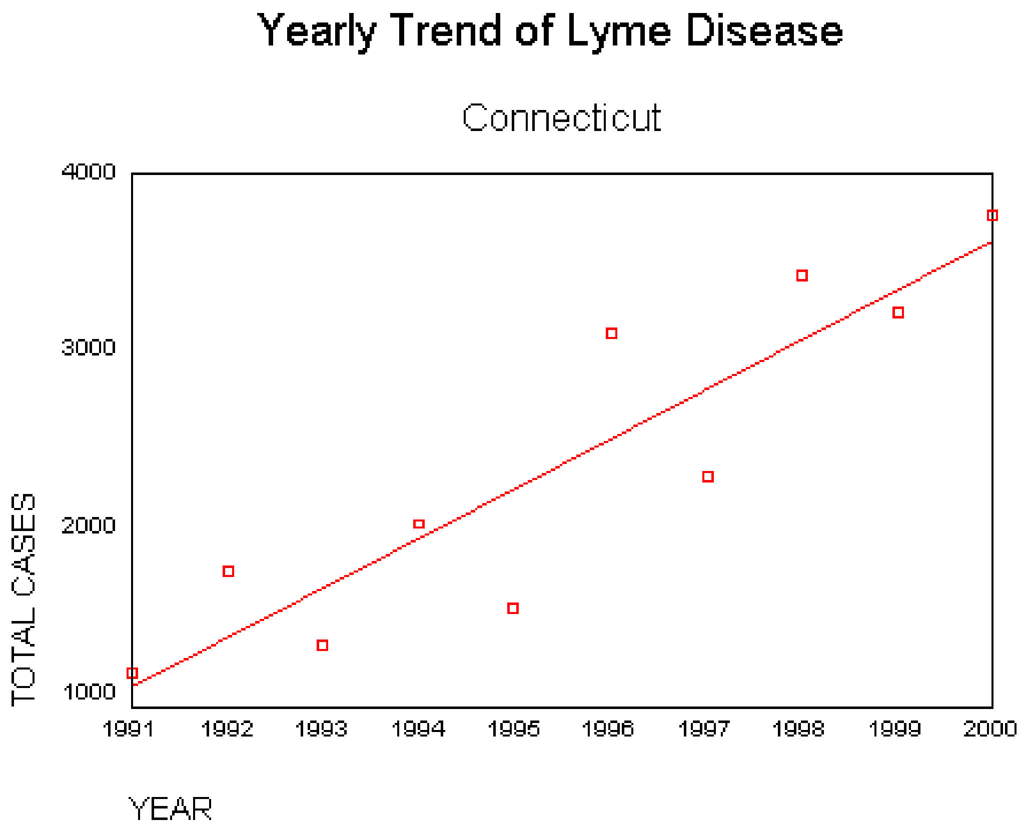

Figure 7: Example of plot and trend line fitted by linear regression (Connecticut) based on total cases for each year for the ten–year period 1991 to 2000.

To examine the relationship between climate and Lyme disease reports, plots are created of average county Lyme cases (1994 to 1999) and average cases adjusted by population were plotted against average county precipitation totals, average temperature, soil moisture surplus totals, soil moisture deficit totals for different monthly time periods. Of particular interest were the three month periods of January, February, March (JFM) and April, May, June (AMJ) because the literature (VanDyk et al. 1996, Yuval and Spielman 1990) suggests that these months should influence infection reports in the following summer. From these plots the potential influence that climate has on the disease can begin to be understood. The spread or range of climatic values plotted against the disease demonstrates this concept. For each three–month period (Figure 8), the time period that is more closely related to the tick and transmission of the bacterium should be the one with the narrowest range of climatic values. Thus, less spread could indicate that the time period is more highly related with high Lyme disease reports.

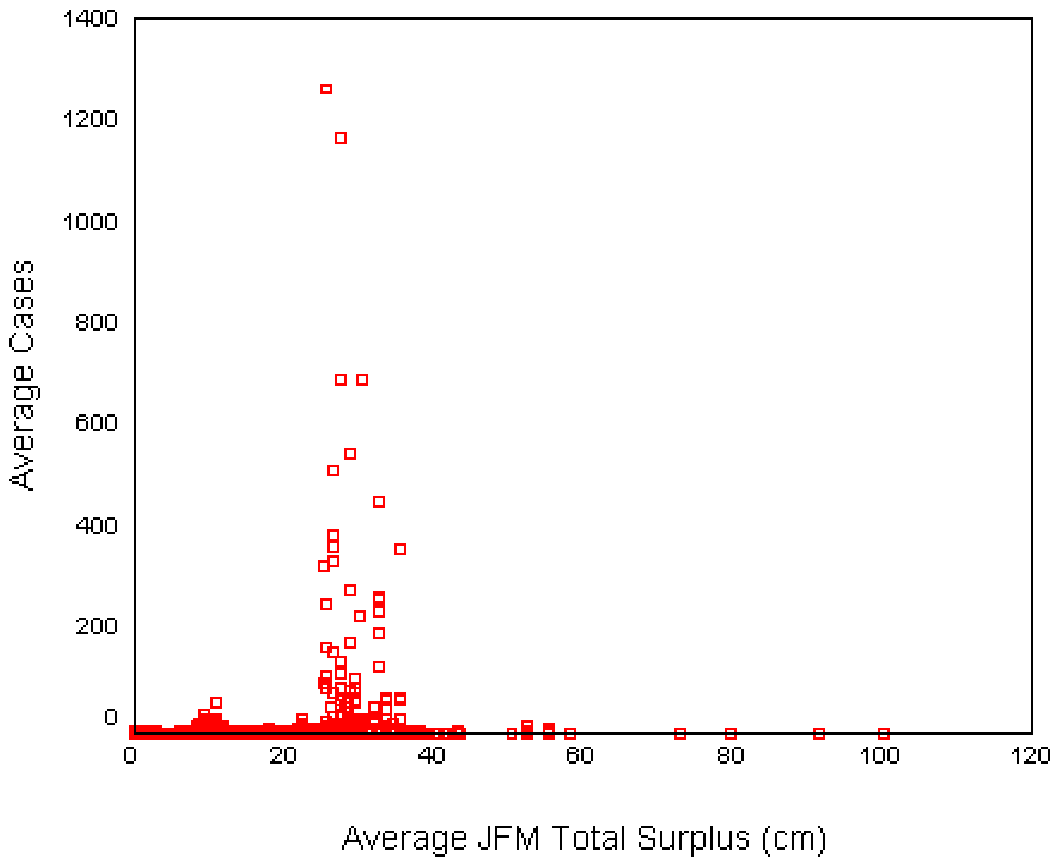

Figure 8: Scatterplot example. Average JFM climate division soil moisture surplus values with corresponding county's average number of cases.

These graphs of average cases plotted against a single climate variable reveal that a "favorable" climate can be associated with counties of both high and low reported cases of Lyme disease. From the "favorable" climate zone, five counties with the highest occurrence of the Lyme and five counties with the lowest occurrence were selected from the database. For these counties, vegetation landuse and population were analyzed to search for additional variables that might be associates with extremely high and low case reports within the "favorable" climate. In addition, this method permitted the landuse characteristics for the high Lyme disease counties in the highly endemic area of the Northeast to be compared to the landuse characteristics of the high counties of Lyme disease in the slightly less endemic area of the Midwest. This analysis was repeated using Lyme disease reports adjusted by population.

Unfortunately, correlation/regression methods are not well suited for this analysis. Consequently a "climate envelope" method will be used. In essence this method attempts to find the upper and lower limits of climatic variables for the counties with high rates of reports. The smaller the envelope, i.e., the lower the range of the climate variables, the better the envelope model is assumed to be. *Surfer* will be used to create these "climate envelope" maps. Lyme disease cases by climate division (both yearly and average) will be placed into classes, which will be represented by symbol, and then plotted against two climate variables instead of the previous one climatic variable. These maps will be created using climate values from both JFM and AMJ time periods. An example of this is shown in figure 9.

Lastly, a "climatic envelope" model will be created to show counties that are within the upper and lower limits of the AMJ climate variables that are found for the counties with greater than 10 cases/100,000 people. These upper and lower limits were found by taking the climate of the counties in the middle 90th percentile range of all counties with greater than 10 cases/100,000 people. The climate model is based upon the equation below:

Predicted "Favorable Climate" = (Range of AMJ Total Precipitation Values) + (Range of AMJ Total Surplus Values) + (Range of AMJ Average Temperature Values)

Counties that fall within the climatic boundaries will be mapped using *ArcView*. This map should show counties that meet the climatic requirements to support at least 10 case/100,000 people, but not all counties within boundaries will show extreme rates of Lyme disease. Without a viable tick–host–human system the disease may be virtually absent.

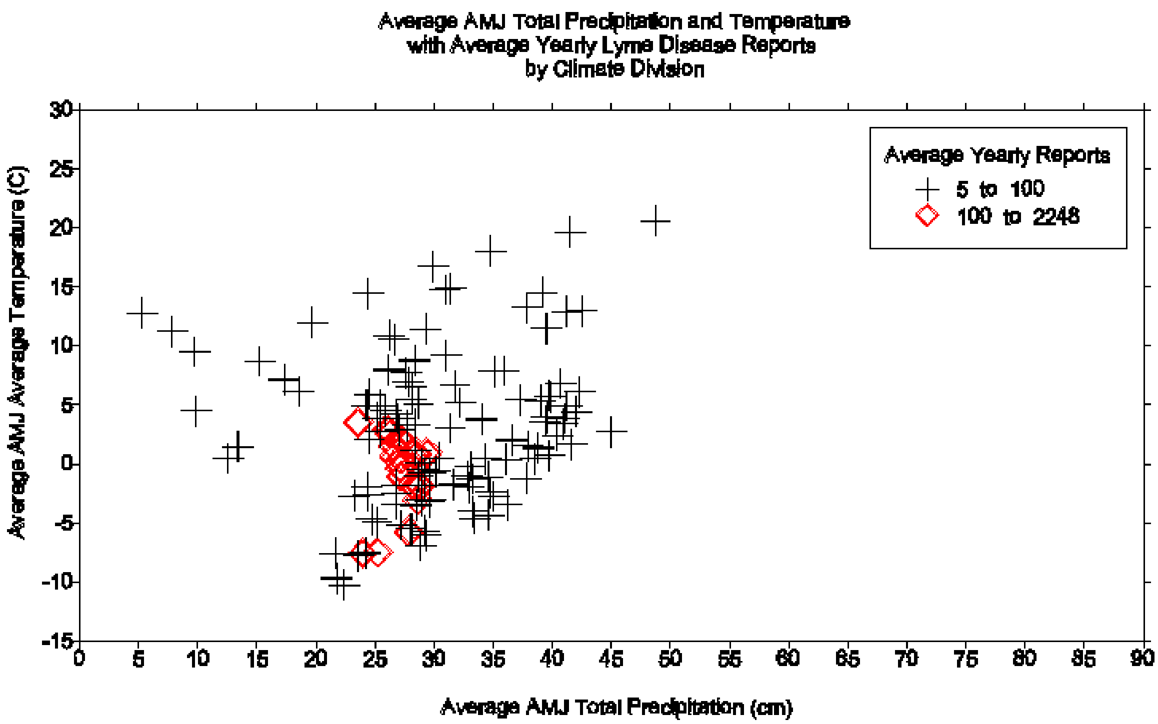

Figure 9: Example of classed Lyme disease cases with corresponding average AMJ precipitation and temperature values.

CHAPTER 4. RESULTS

4.1 Introduction

In the past, research on Lyme disease has been confined to a broad description of its spatial and temporal distributions or has hypothesized the impact that given meteorological and/or climatic variables have on the survival and population dynamics of the tick or bacterium, itself. This study attempts to first give a more precise description and mapping of seasonality by identification of the peak month(s) of occurrence for every state in the contiguous U.S.

The literature states that Lyme disease has been increasing over the past ten years in the U.S. (Keirans et al 1996), but this has not been verified recently and no account of each individual state has been determined. This research will identify the year–to–year variability of the disease for every state in the U.S. for the period of 1991 to 2000 and map the trends. Through these first two objectives, the degree to which weather and climate influences Lyme disease may begin to be revealed.

In addition, to this descriptive analysis of the disease, the relationship between the population of a county and the number of yearly reports for that county will be investigated. Population creates a bias in the interpretation of the raw Lyme disease statistics; therefore, Lyme disease reports adjusted by population will be used as well as the raw data. Additionally, the degree to which a county's population spans the rural to urban spectrum will be related to disease reports.

Lastly, determining the relationship, if any, that climate has on the spatial distribution of Lyme disease will be attempted. Finding this control is confined to testing the climatic variables of the two time periods (JFM and AMJ) for their influence on the Lyme disease season that follows. Once a time period has been evaluated as more influential in the transmission of Lyme disease, highly endemic areas of Lyme disease will be matched to the climatic variables that they correspond with by using a "climatic envelope" method. Lastly, a "climatic envelope" model will be created which will combine all the climate characteristics that correspond with highly endemic areas. This will be mapped to show the most "favorable" area for Lyme disease to occur with respect to the climate. It must be noted that the macroclimate that coincides with counties with high case rates shows only where the disease is more favorably accepted. This means that the disease may not become epidemic in areas within the climate zone if the other required components of the disease do not exist in that region (i.e., sufficient tick, host, and human populations). Ultimately, all ingredients necessary for the transmission of the disease from host to vector to human must be sufficiently abundant in regions where the climate is most optimal and the absence of one means the cycle of transmission will not be completed.

4.2 Results of Descriptive Analysis

4.2.1 Results of Seasonality Analysis

The analysis of the number of reports per month for the entire 48 contiguous states for the ten–year period (1991 to 2000) reveals that for an average year, the highest number of reports occurs in August (2295 cases) with slightly fewer occurring in July (2148 cases); interestingly, a secondary, lesser peak occurs in December (1437) (Figure

10). Computations for each state individually show considerable variability in the seasonality of Lyme disease across the U.S. (Figures 11-13).

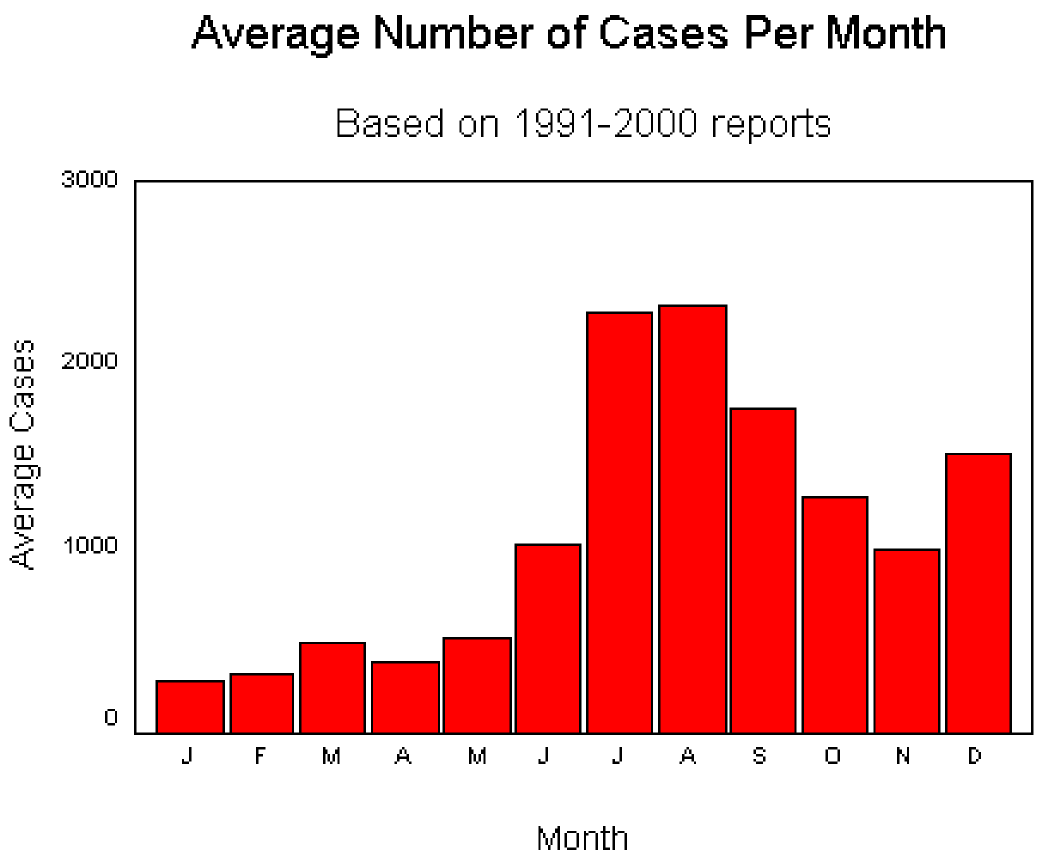

Figure 10: Average number of cases per month for the 48 United States based on Lyme disease reports from 1991 to 2000.

Figure 11 shows the month and secondary peak month for each state (i.e., Ad means an August primary peak with a secondary, lesser peak in December). Although the peak month is highly variable from state to state, figure 11 does illustrate some areas of spatial cohesion for seasonality across the U.S., primarily in the west and south. This is especially true for the primary, peak month with the western and southern states showing a primary peak predominately in August. It is noteworthy that an obvious secondary peak occurs in eight of the 48 contiguous states including California, Illinois, Maryland, Massachusetts, New York, and Pennsylvania and occurs in the winter months of either December or January. Two other states, Maine and Texas, also show a secondary peak, although it occurs in the summer months of July (Maine) and August (Texas).

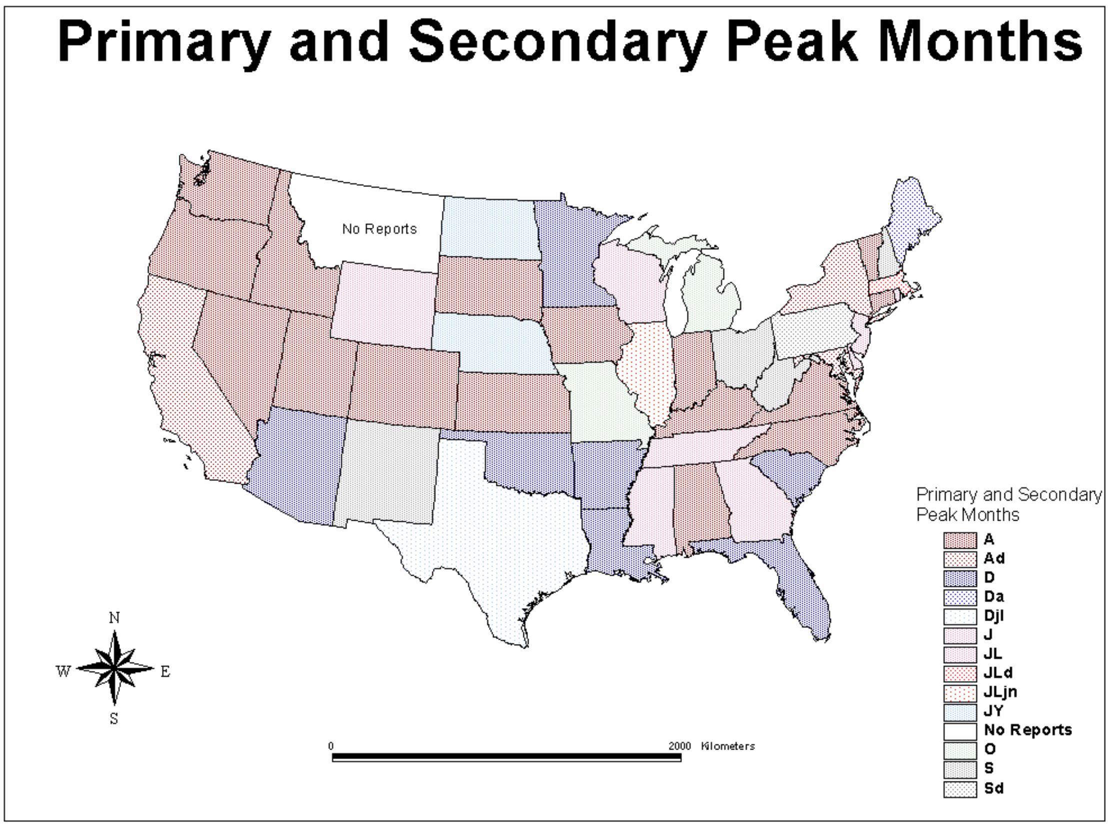

Figure 11: Results of seasonality analysis given by month based on Lyme disease reports from 1994 to 1999. A capital letter indicates primary, peak month while a lower case indicates secondary peak (A is August, D is December, J is June, JL is July, JY is January, O is October, and S is September).

The peaking of Lyme disease by state is also mapped by two other means besides monthly including traditional seasons (winter, spring, summer, and fall) and warm (March through August) / cold (September through February) seasons (Figures 12 and

13). Both maps show that the primary and secondary peaks reveal a similar, highly variable pattern with some spatial cohesion of peak months. The spatial cohesion usually occurs in the west from the coastal states inland up to, but not including, the Great Plain states and also to a smaller extent in the south. For all maps, the combined region of the Mid–Atlantic and Northeast is one of the more variable regions geographically with the peak month occurring in the fall, winter, or summer.

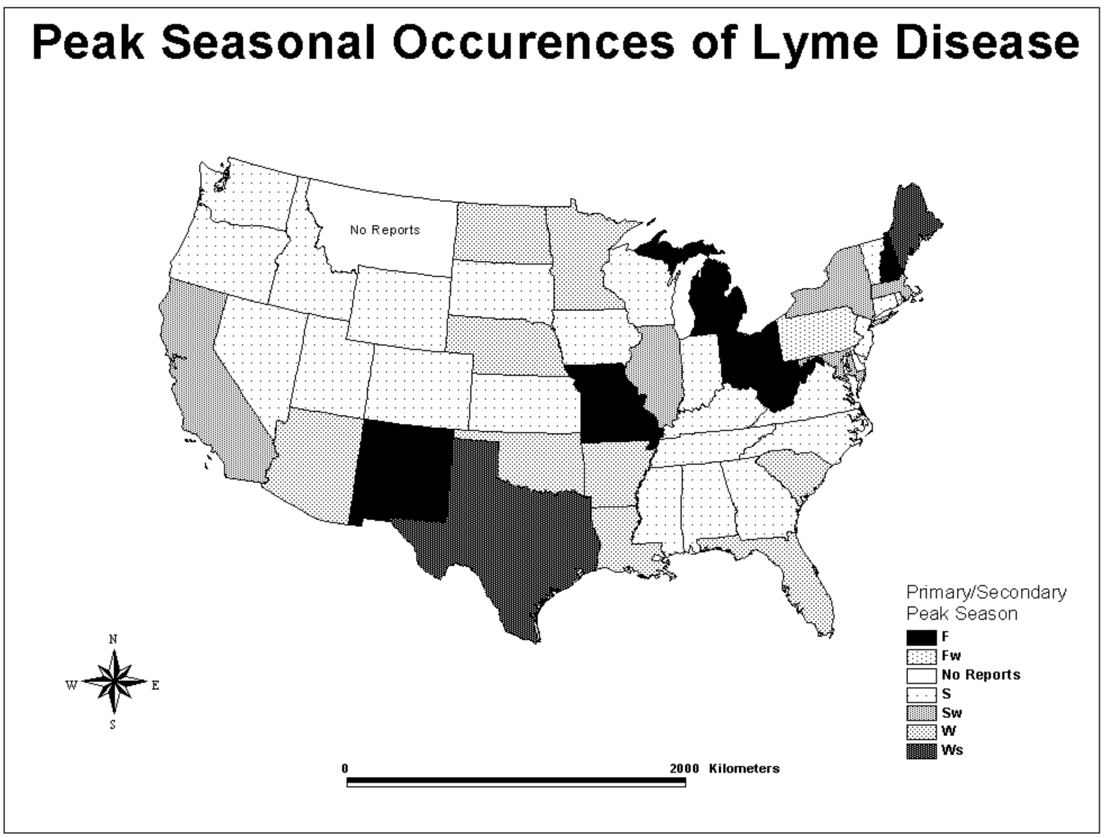

Figure 12: Results of seasonality analysis given by season based on Lyme disease reports from 1994 to 1999 (F is fall, S is summer, and W is winter).

It is generally agreed upon in the literature that Lyme disease outbreaks in the Northeast tend to strike in the summer months with the peak month being July (WebMD Medical Library 22 March 2001, Gubler et al., 2001); therefore, the conclusions found here vary from previous conclusions because of their specificity and differing data periods. Through this region, the peaking does occur generally in summer months, but the month changes across the

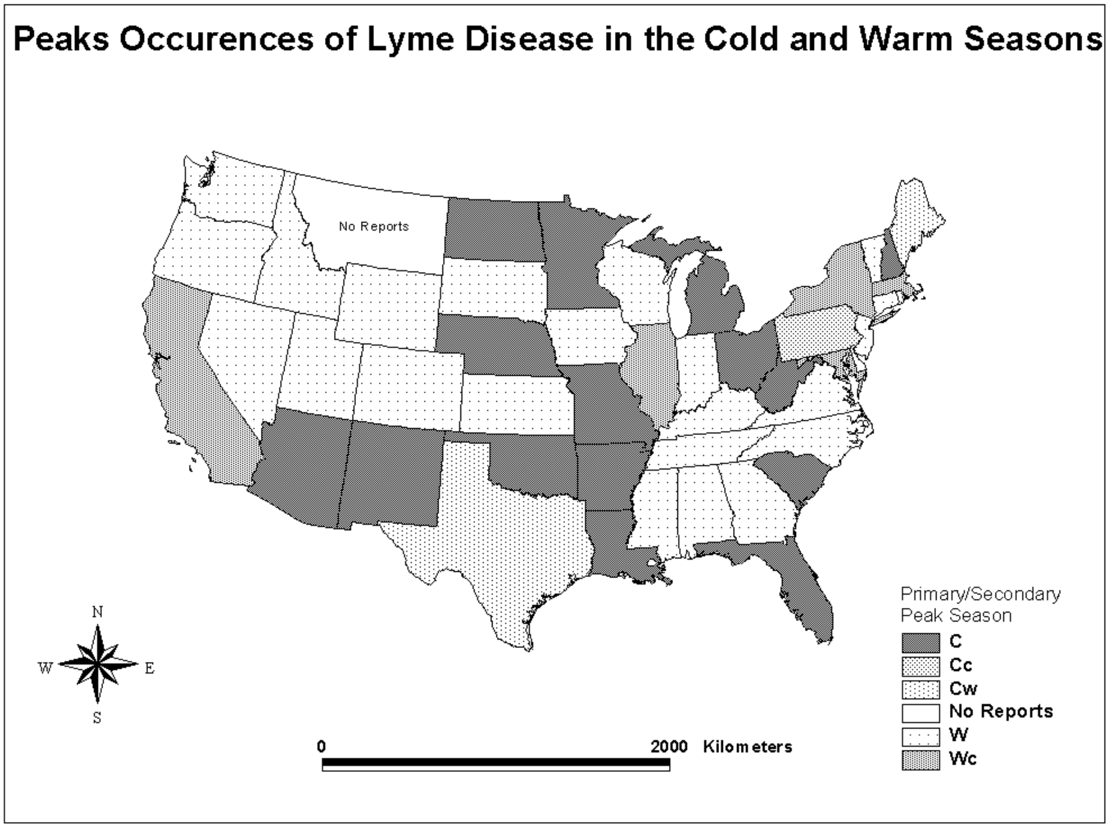

Figure 13: Results from seasonality analysis given by warm and cold seasons based on Lyme disease reports from 1994 to 1999 (C is cold season and W is warm season).

region. In addition, the literature has stated that western states have high occurrences from January to May and non–coastal western states have high occurrences from November to April, with no peak month being reported (WebMD Medical Library 22 March 2002). The results here show that August is the dominant month of peak reports in the slightly endemic area in the west (i.e., California, Oregon, and Nevada) with only

California having a secondary peak in December and the other endemic region of Minnesota and Wisconsin having a peak in December and September, respectively.

These findings, which are based on Lyme disease reports from only 1991 to 2000, show that it is difficult to regionalize and/or generalize the seasonality of Lyme disease because of its state–to–state variability. It must be noted that the discrepancies between these results and previous results may be due to different data periods (i.e., longer periods of record or older/more recent periods of record) being used.

4.2.2 Results of Trend Analysis

To determine the true trend of this disease across the U.S. over the years 1991 to 2000, each state's annual variability is analyzed. Using the slope of the regression line that is fitted to the yearly values, the trend of the disease can be seen to be decreasing, increasing, insufficient cases, or no trend (Figure 14). To accurately determine the slope of the line, a correlation matrix of total cases and year is first produced for each of the 48 states. From this, the Pearson's r–value or correlation coefficient is found. If the relationship is determined to be statistically significant at a 95 percent confidence interval using a two–tailed test, the state is evaluated as either significantly decreasing or increasing in Lyme disease cases over the ten years. However, many states show extreme variability from one year to the next, therefore, the r–value will not be statistically significant. This non–significant relationship is due to the fluctuation of Lyme disease reports over the ten–years, which makes it difficult to distinguish an increasing or decreasing pattern. States with this type of pattern are concluded to have no apparent trend of Lyme disease cases. Lastly, states that do not have more than ten reports for all years are assessed as having no apparent change in trend because of an insufficient number of cases.

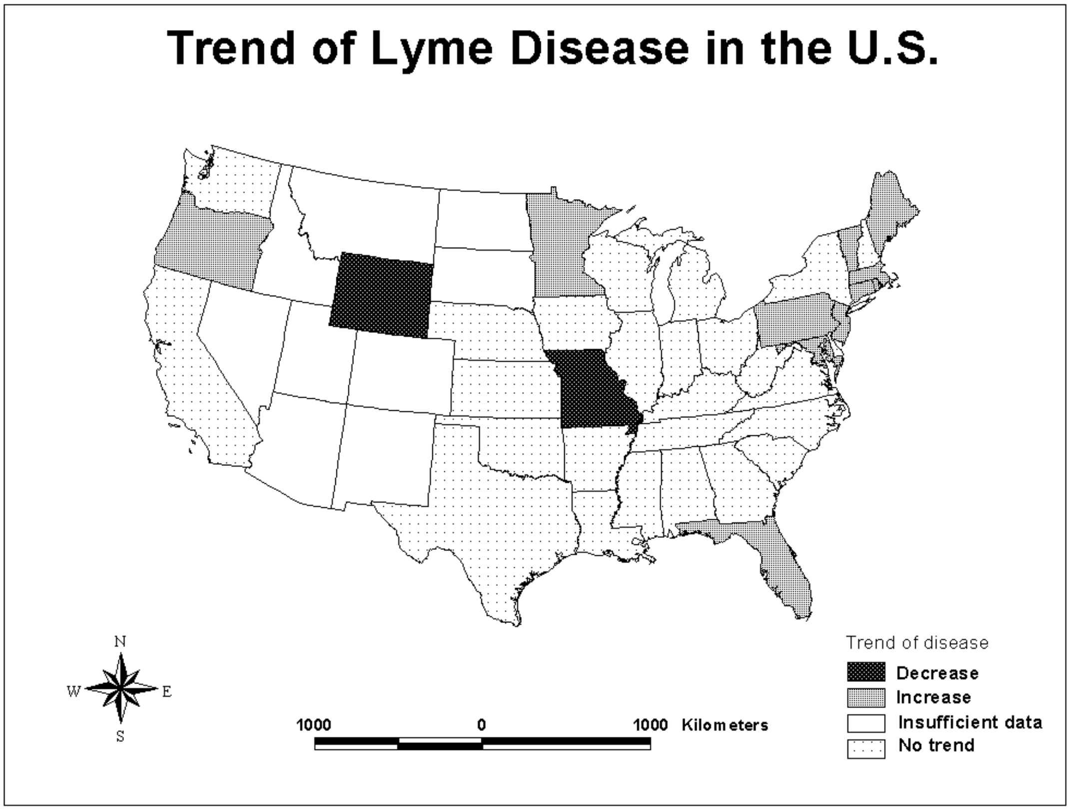

Figure 14: Trend of disease for each contiguous state of the U.S. based on Lyme disease reports from 1991 to 2000.

States that have a statistically significant increasing trend of Lyme disease cases at the 0.05 significance level include Connecticut, Florida, Maine, Maryland, Massachusetts, Minnesota, New Jersey, Oregon, Pennsylvania, Rhode Island, and Vermont, while statistically significant decreasing states include Missouri and Wyoming. First and foremost, the states that are increasing in Lyme disease cases are predominately in the endemic Northeast: states with high reports are experiencing even higher reports. Also, the disease is increasing in Minnesota, which is located in the slightly endemic secondary region of the Upper Midwest. This increase, primarily in the present endemic areas, shows that this disease is increasing in the U.S. and may continue in the future. Interestingly, two states that are increasing significantly in cases are Florida and Oregon, which suggests that this disease is spreading in its spatial distribution. From figure 14 it is obvious, however, that for most of the U.S. states with more than ten reports/year the Lyme disease trend is fluctuating from one year to the next with no statistically significant trend. Because of the variability from year–to–year, these areas should be monitored in the future for an increasing or decreasing trend, especially in regions where a suitable tick–host–human system may be present.

4.3 Results of Population Analysis

4.3.1 Results of Population Versus Raw Lyme Disease Cases

It is hypothesized that there is a population value that is too low and a population value that is too high to allow Lyme disease to become an epidemic in that county or region. This is because of either the lack of host/tick populations in high population counties with little rural areas or lack of human population from low population counties with large amounts of rural landuse. Ultimately, this points to the conclusion that population is only one of the required entities for a county to contain a high amount of Lyme disease cases because of the necessity to have all the required "ingredients" in the transmission cycle.

This research shows that the population of a county is related to the number of Lyme disease reports for that county, but it is not a linear relationship (i.e., Lyme disease reports do not increase/decrease with an increase in population). Instead, counties with high numbers of Lyme disease reports (i.e., >100 average cases a year) generally occur within a range of population estimates. A graph of Lyme disease reports versus population (Figure 15) shows that as population greatly increases the number of reports decrease. Although, when population and only counties with an average number of cases greater than ten are graphed, it is more evident that it is not so clear a relationship.

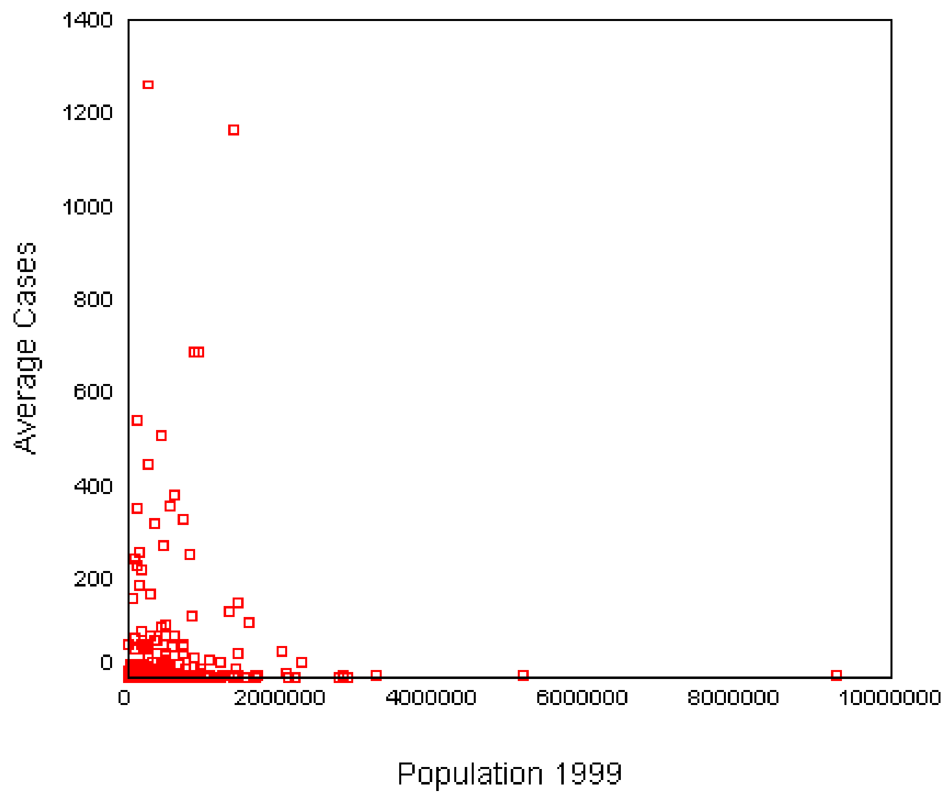

Figure 15: Average cases of Lyme disease per county based on 1994 to 1999 reports plotted with population estimates (1999).

The second population plot (Figure 16), which shows only the counties with more than ten average cases, a county with a high Lyme count (i.e., >100 average cases per year) can have a population anywhere between 63,099 and 1,559,756. In addition, there are many counties that are within this range that have less than 100 cases, which suggests that the population of a county is only one factor responsible for the success of the transmission of Lyme disease. Figure 16 also shows that there are two distinct outlier counties having the two highest average cases, but one with a relatively smaller population estimate of 266,809 (Dutchess County, NY) and one with a larger population estimate of 1,379,690 (Suffolk County, NY). From this figure it can be concluded that the general statement that Lyme disease reports decrease with an increase in population is not exactly true, but instead there is a wide range of population values where Lyme disease can reach epidemic proportions.

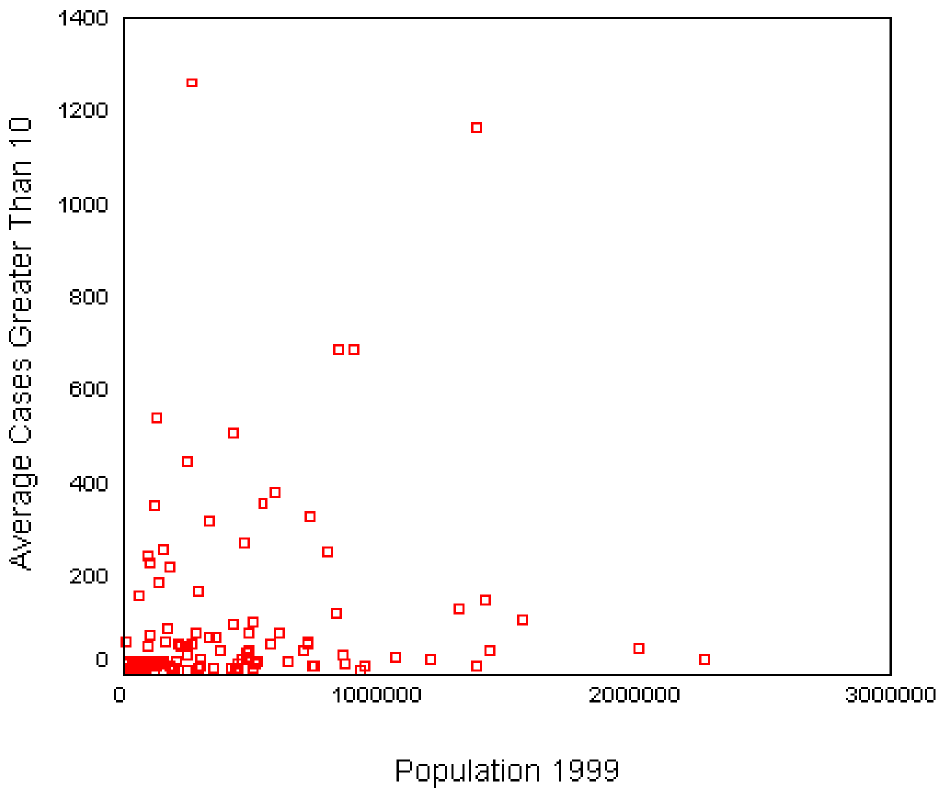

Figure 16: Counties with greater than ten average cases of Lyme disease plotted with population estimates (1999).

4.3.2 Results of Population Density Versus Raw Lyme Disease Cases

Population density plots show the same pattern as the population plots except a county with a low population density can support a high number of Lyme disease cases (Figure 17 and 18). The two outliers, Dutchess and Suffolk Counties, NY, are both showing low population densities with the Suffolk County portraying a higher population density and a lower number of Lyme disease reports than Dutchess County. No firm conclusion can be made from these figures except the generalization that extremely high population counties with possibly little to no rural area cannot support high cases of Lyme disease because of their insufficiency to maintain the vector and/or the host of the disease because of the lack of a suitable habitat. The population density graphs point to the same conclusion; places with high population densities (i.e., large number of people per square mile) have very low Lyme disease reports because there are little suitable habitats for the tick/vector to populate. Although this conclusion is only speculation at this point, it is reasonably sound.

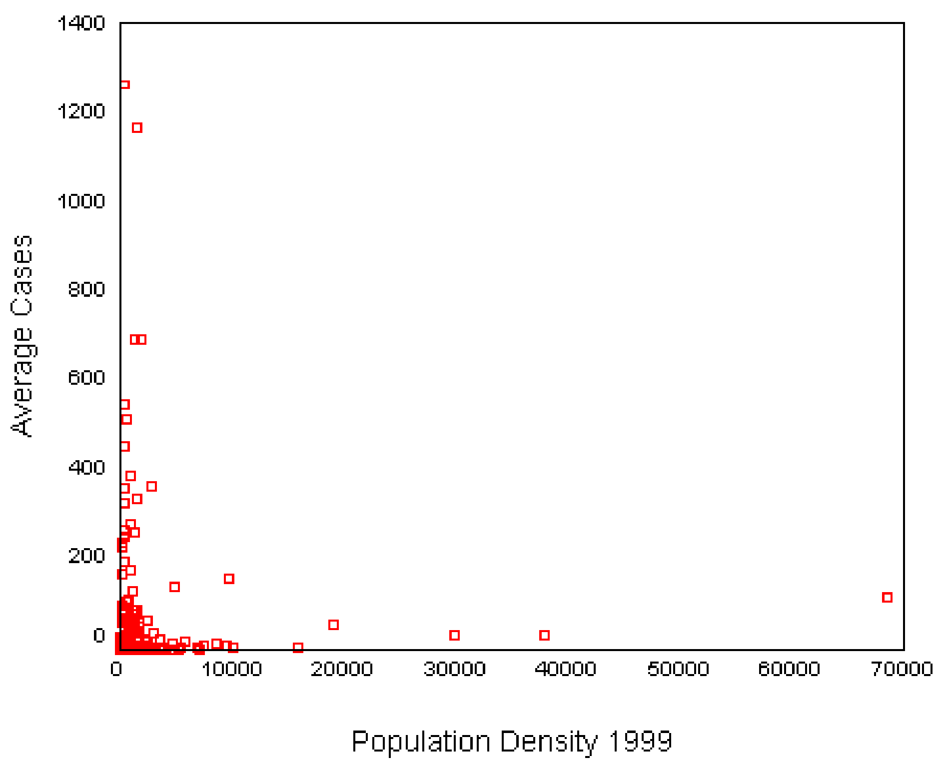

Figure 17: Average cases of Lyme disease based on 1994 to 1999 reports plotted with population density estimates (1999).

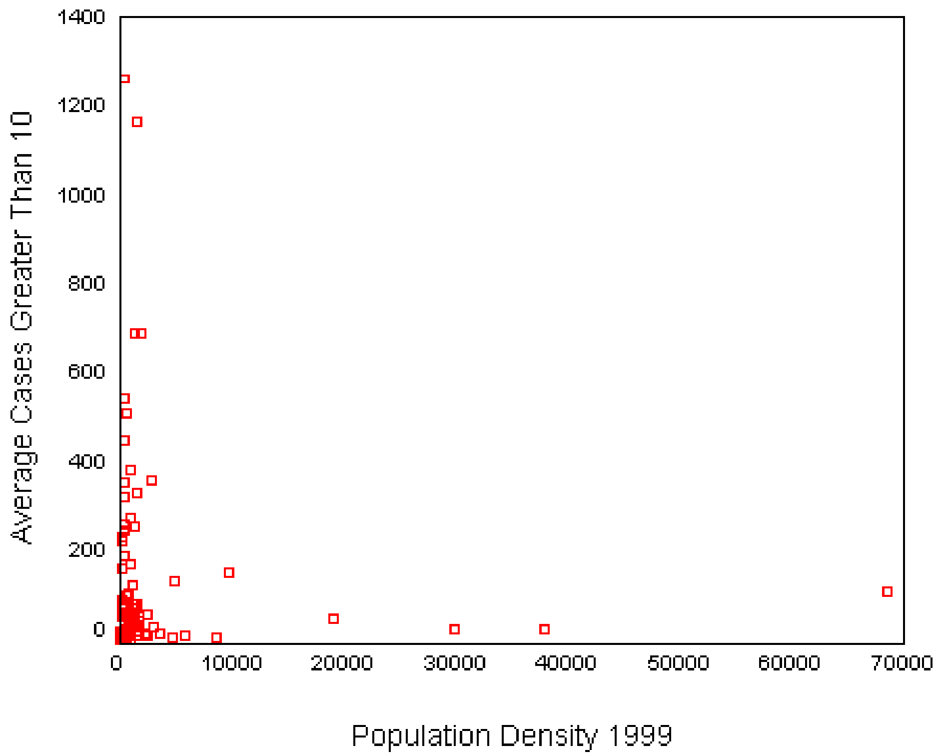

Figure 18: Counties with greater than ten average cases of Lyme disease reports plotted with population density estimates (1999).

4.3.3 Spatial Distribution of Lyme Disease Adjusted by Population/Population Density

The spatial distribution of Lyme disease adjusted by population and population density are mapped so that any changes that occur from the original map can be seen (Figures 19 and 20). Figure 19, the map of cases adjusted by population, shows that the three areas located in the Northeast, Upper Midwest, and far west still contain the counties with the largest rates of Lyme disease reports for an average year. Although some counties in states located in the middle of the county (i.e., Texas, Oklahoma, Arkansas, Missouri, and Kansas) become more prominent because of the large amount of cases reported for their low population estimates. In addition, the Upper Midwest endemic region becomes more pronounced as well because of their high Lyme disease rates.

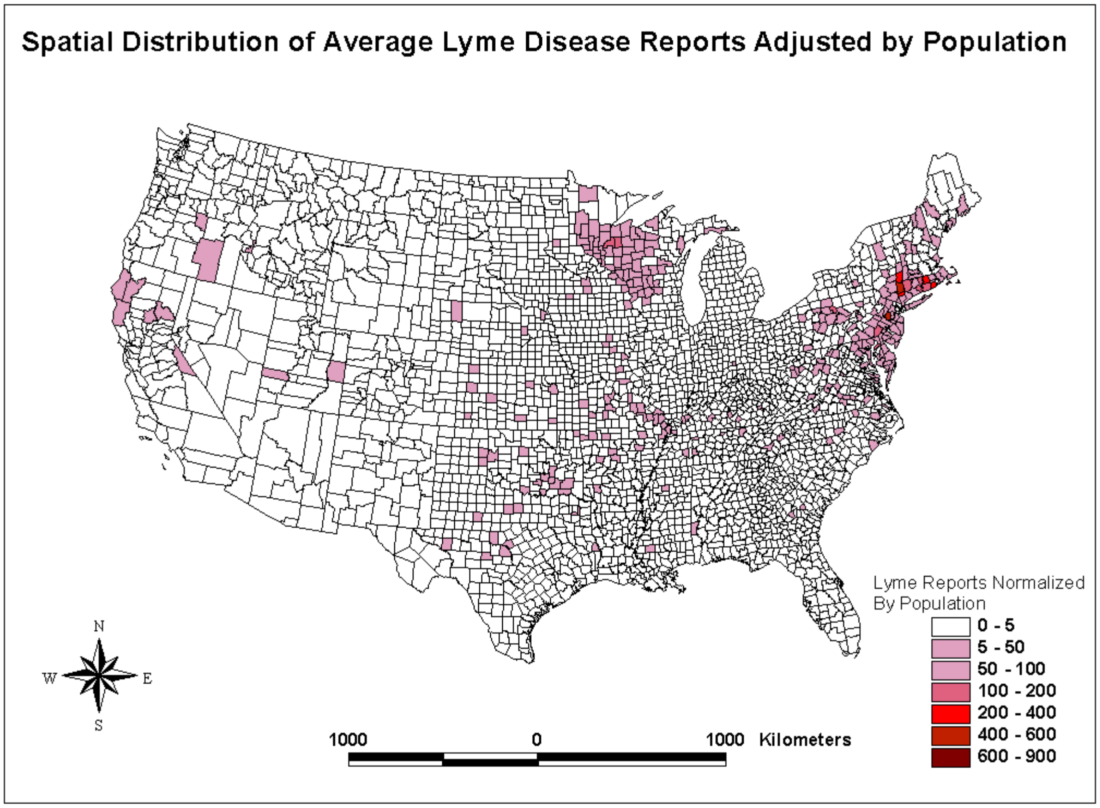

Figure 19: Spatial Distribution of Average Lyme disease reports by county normalized by population based on data from 1994 to 1999.

Figure 20, the map of the cases adjusted by population density, also shows the three areas as being the regions of focus regarding the disease, with the Upper Midwest region again becoming more noticeable because of the high number of reports for their population density. In the Northeast, counties in Maine and New Hampshire begin showing up as having a significant amount of Lyme disease cases for their population density as well as counties in the far west and west. Population clearly changes the previous spatial distribution of raw Lyme disease cases across the contiguous U.S. and adjusting for this bias shows that the disease may be more of a threat in regions such as east central Minnesota and northwestern Wisconsin, which were previously seen as only slightly endemic. Due to the relationship between population and Lyme disease cases for a county, further analyses will use cases adjusted by population in order to adjust for any population biases. At times, results will be reported for analyses done for both raw cases and population–adjusted cases per county.

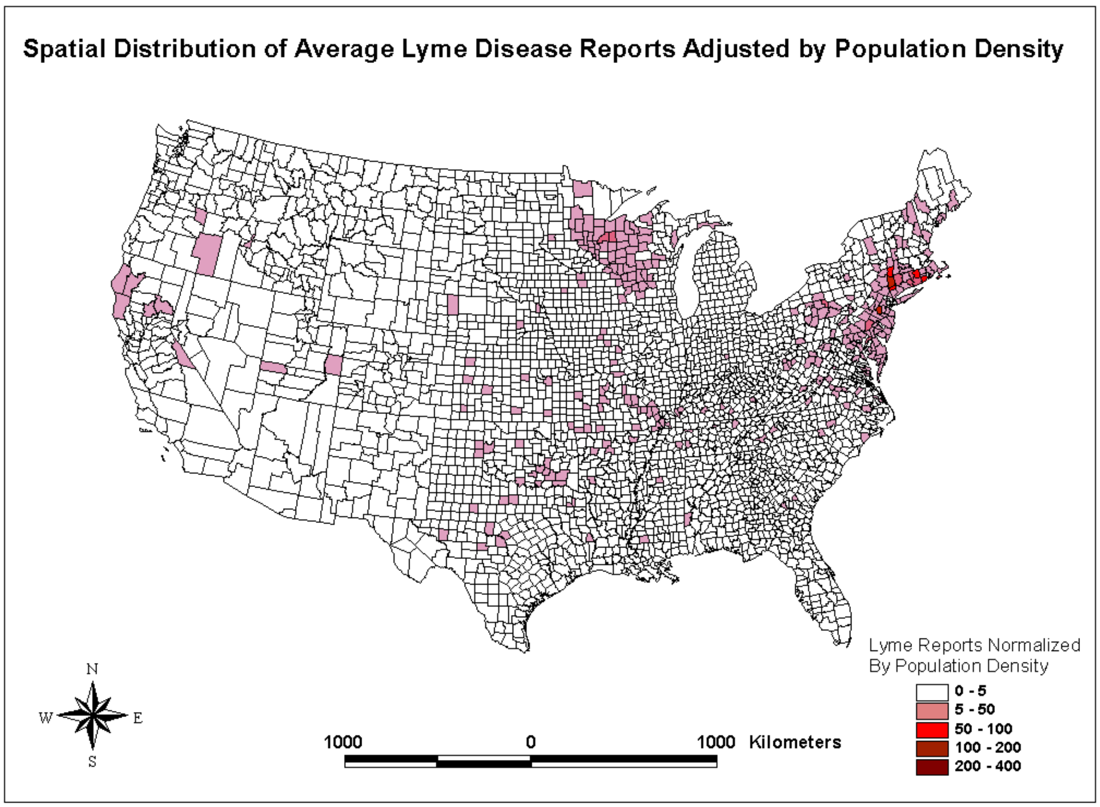

Figure 20: Spatial distribution of average Lyme disease reports by county adjusted by population density based on data from 1994 to 1999.

4.4 Results of Climatic Influence Analysis

4.4.1 Introduction

It is also hypothesized, based on suggestions from the literature, that macroclimatic conditions in the six months prior to the peak Lyme disease season of July and August have an affect on the Lyme disease of that upcoming season. Previous literature has indicated the importance of the winter and spring climate conditions on the survival and population of the nymphal tick (VanDyk et al., 1996). It is assumed, therefore, that either late winter to early spring or late spring to early summer time periods should have some degree of a relationship, because they precede the overall peak season during July and August.

Tests done in the earlier stages of this research indicated that a climatic–disease relationship would produce poor results using average yearly values of climatic variables. This is due to the excessively broad temporal match and the large number of climatic regimes experienced across the 48 states. Instead the tests indicate that three–month, lagged periods should create a better match with yearly Lyme disease reports. A county's climatic characteristics averaged over a year is too long a period and will show little or no relationship since the disease largely occurs in only three months out the year. Additionally, the overall peak season of this disease will be used for this analysis instead of each states individual peak month, because June, July and August are the months that the disease peaks in the endemic areas.

A clue into determining which three–month time period is most influential on the Lyme disease season can be initiated by evaluating the graphs which plot of average cases (by county) against the single climatic variables. These graphs show clearly that traditional correlation and regression techniques cannot be used in this analysis. It is assumed, therefore, that the degree of spread of the disease across a lagged climatic variable is an indirect indicator of the influence that it has on Lyme disease cases. A small spread should indicate a stronger relationship than a larger spread. Of course, it must be noted that these plots will all contain a clustering of high cases because of the rather narrow geographic distribution of endemic areas of the disease.

4.4.2 Climatic Relationship for Counties using Raw Lyme Disease Case Data

To determine whether there is a relationship between county Lyme disease cases and climatic variables, average yearly cases from every county (including counties with zero reports) were graphed against their corresponding average total precipitation, average temperature, total soil moisture surplus, and total soil moisture deficit values for the following lagged time periods; JFM (January, February, March) and AMJ (April, May, June) so that any type of relationship (i.e., linear, non–linear) between the variables can be ascertained (Figures 21-28). In addition, both periods will be cross–analyzed to determine the time period with a better relationship with the summer Lyme disease season.

Figures 21, 22, 23, and 24 show graphs of raw average disease cases by county plotted against one climatic average for January, February, and March. The plots for precipitation (Figure 21) and surplus (Figure 23) both show a primary peak and a small secondary peak. The larger peak represents the northeastern endemic region and the smaller peak, the Upper Midwest. In JFM the Midwest has only about 10.16 cm of precipitation while the Northeast has about 33.02 cm of precipitation.

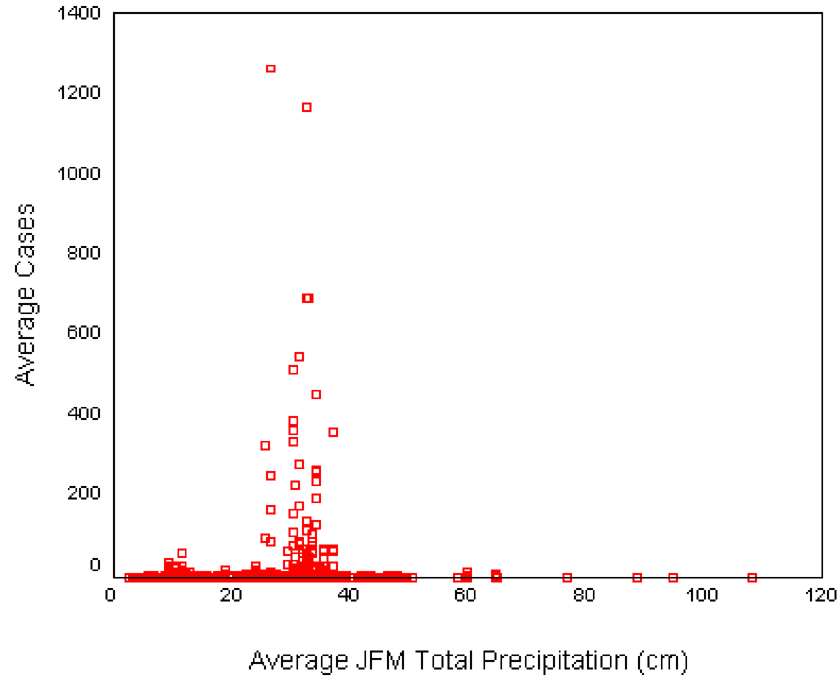

Figure 21: Plot of average cases by county with corresponding average JFM precipitation values based on data from 1994 to 1999.

The dual peaks shown on the JFM precipitation and surplus plots are not so clearly evident for the JFM temperature plot (Figure 22). Furthermore, the JFM deficit plot (Figure 24) shows zero or near zero values for counties with more than 10 cases/year.

Figures 25, 26, 27, and 28 show graphs of raw disease reports by county plotted against one climatic average for April, May, and June. The plots for precipitation (Figure 25), temperature (Figure 26), and surplus (Figure 27) show only one, primary peak. The absence of the secondary, smaller peak found in the JFM graphs shows that the climatic conditions during AMJ for both endemic areas are similar.

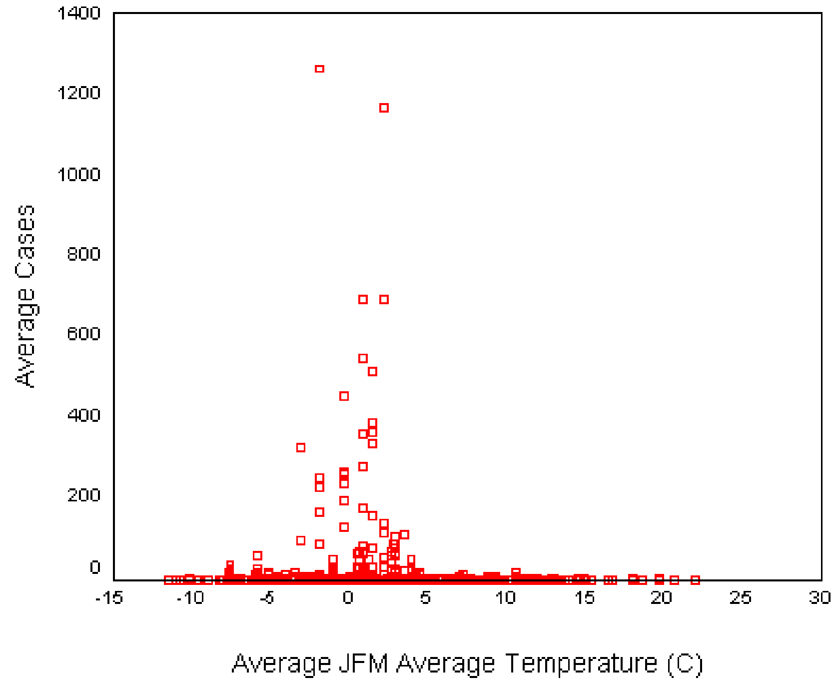

Figure 22: Plot of average cases by county with corresponding average JFM temperature values based on data from 1994 to 1999.

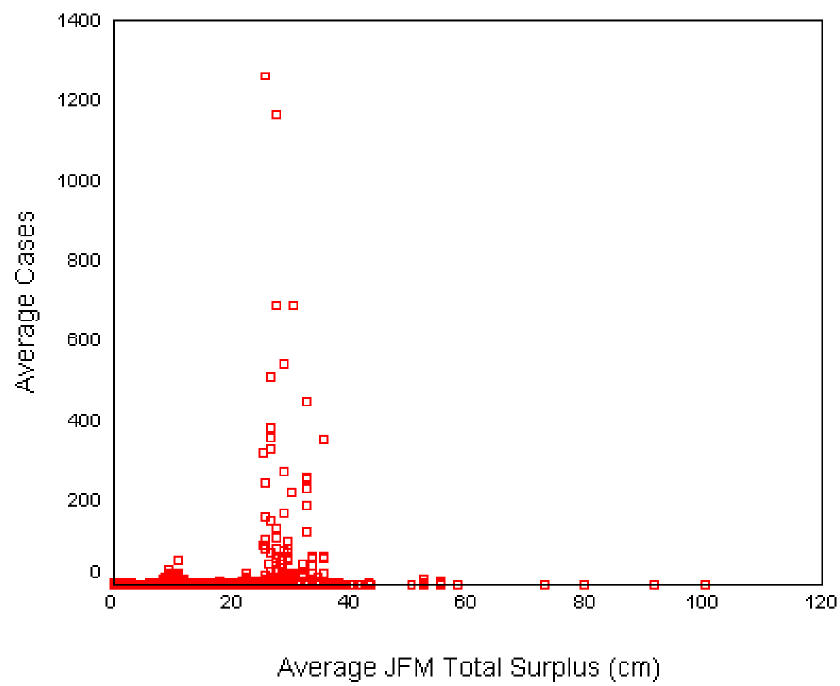

Figure 23: Plots of average cases by county with corresponding average JFM soil moisture surplus values based on data from 1994 to 1999.

The AMJ precipitation graph (Figure 25) shows a very tight cluster of values, whereas, the temperature and surplus graphs (Figures 26 and 27) show a wider range of climatic values. Similar to the JFM deficit graph, the AMJ deficit graph (Figure 28) shows values only slightly larger than zero for all of the counties with more than 10 cases/year.

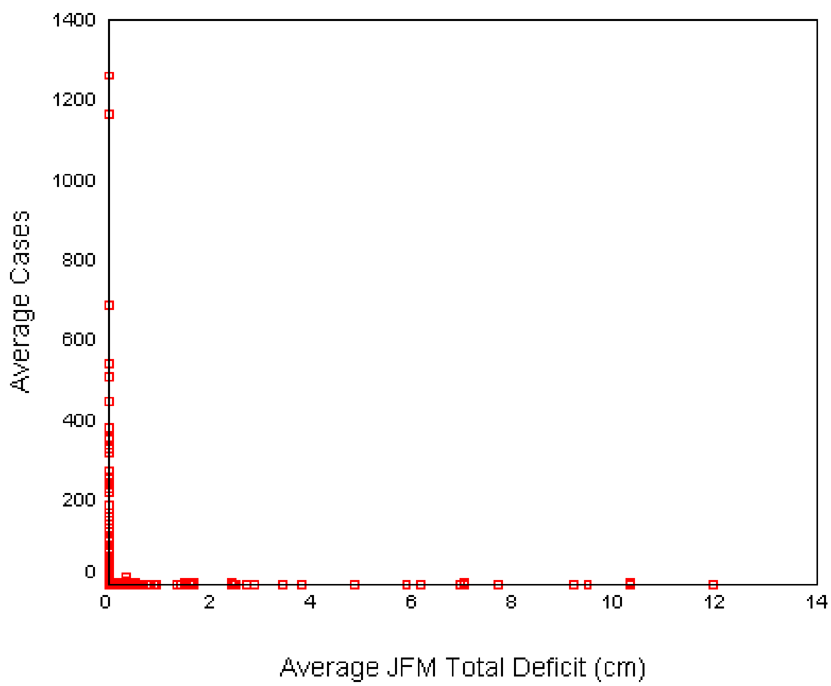

Figure 24: Plot of average cases by county with corresponding average JFM soil moisture deficit values based on data from 1994 to 1999.

A comparison of the JFM graphs to the AMJ graphs shows that the three–month period of AMJ has a smaller degree of spread of its plots for precipitation, temperature, and surplus. This shows that the AMJ time period may have more of a control on Lyme disease than does the JFM period. Furthermore, not only is the spread smaller, but also there is an absence of a secondary, lesser peak located in lower values of climatic

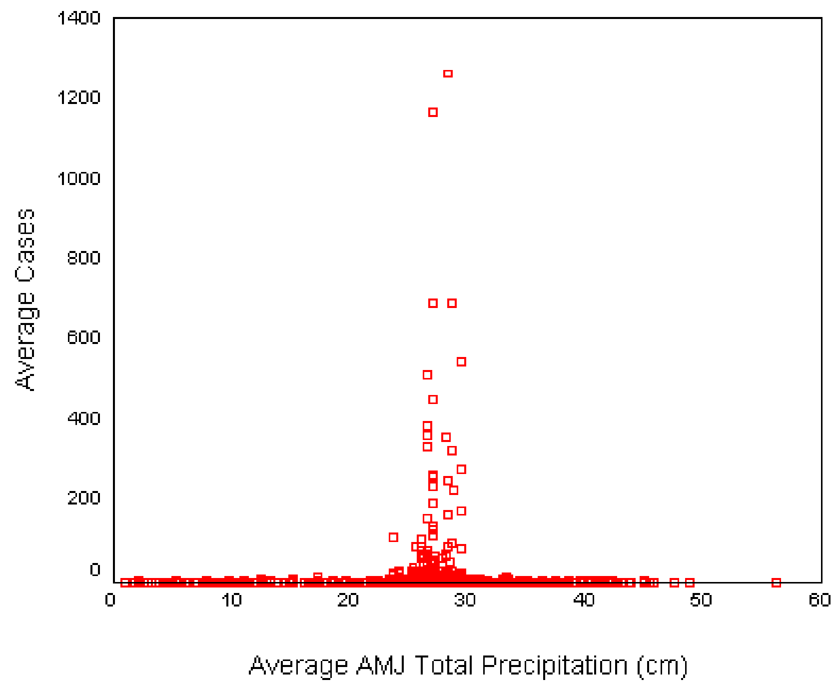

Figure 25: Plot of average cases by county with corresponding average AMJ precipitation values based on data from 1994 to 1999.

variables for all plots. This secondary peak shown on figures 21 and 23 corresponds to the smaller endemic area in the Upper Midwest (Minnesota and Wisconsin). From these plots it can noted that the Upper Midwest region has a colder and dryer winter compared to the northeastern winter. Interestingly, figures 25-28 for the AMJ time period show that the regions are nearly the same with respect to their AMJ values for precipitation, temperature, and soil moisture surplus. This suggests that there is indeed a core climatic zone, which favors the host–vector system for Lyme disease. The AMJ time period seems more closely related to Lyme disease reports than the JFM period since it directly precedes the overall peak occurrence season of the disease. Furthermore, the AMJ time period coincides with the peak activity of the nymphal tick (Yuval and Spielman 1990).

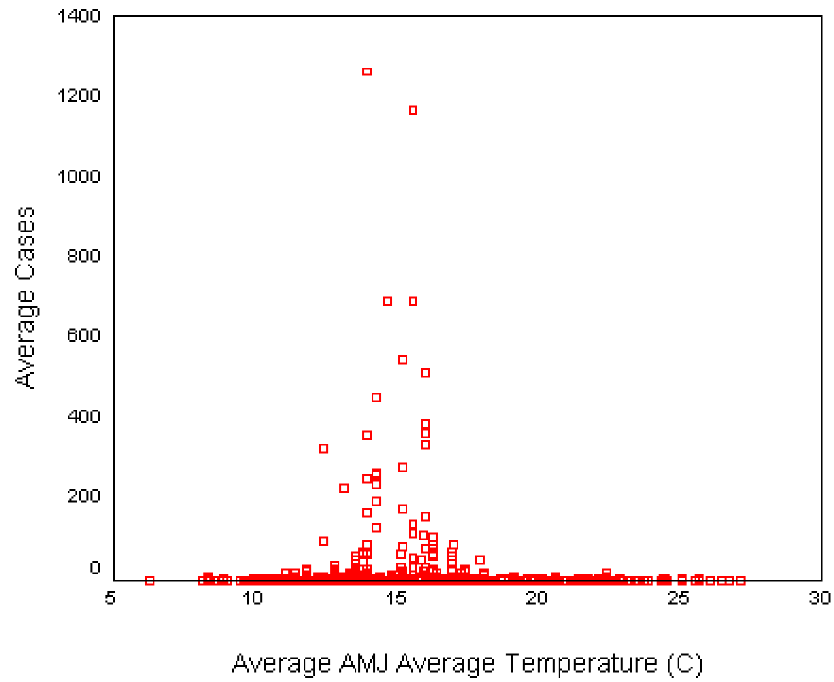

Figure 26: Plot of average cases by county with corresponding average AMJ temperature values based on data from 1994 to 1999.

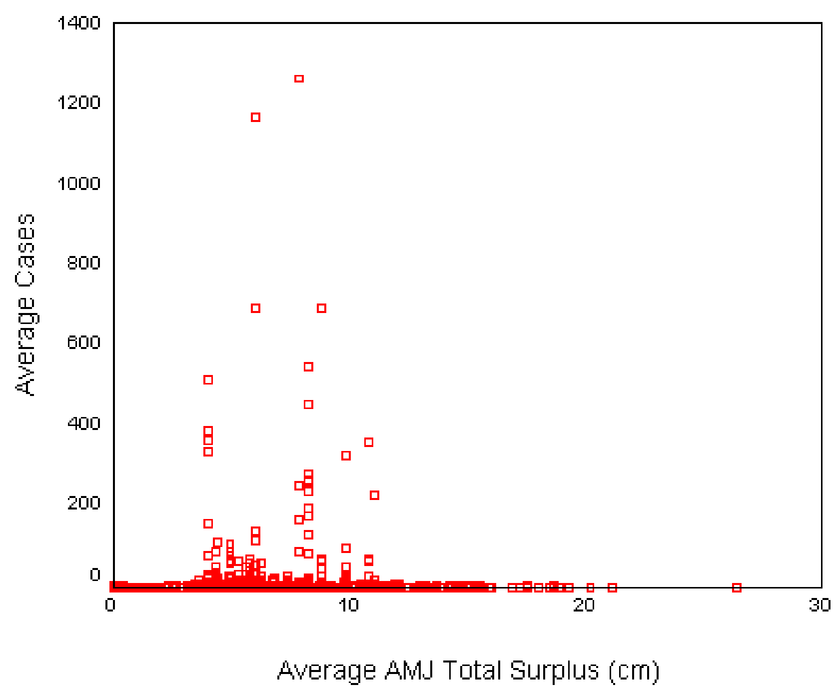

Figure 27: Plot of average cases by county with corresponding average AMJ soil moisture surplus values based on data from 1994 to 1999.

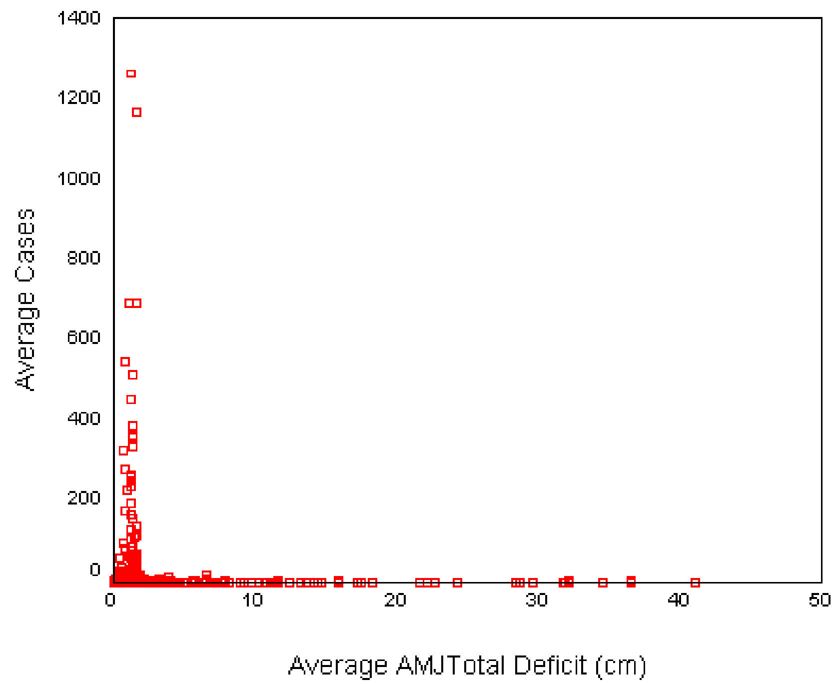

Figure 28: Plot of average cases by county with corresponding average AMJ soil moisture deficit values based on data from 1994 to 1999.

For each of these three–month lagged periods, the majority of the counties in the U.S. have a deficit of zero, or deficits of only a few inches. They are "moist" counties in late winter and early spring. Some of these counties have very low number of average Lyme disease cases but others are in the highly endemic area of Lyme disease. By contrast, more of the counties with deficits greater than approximately 5.08 cm have zero or very low average yearly reports of Lyme disease. It is assumed that moist environments favor the Lyme disease vector–host system.

4.4.3 Climatic Relationship for Counties using Population–Adjusted Lyme Disease Case Data

In addition to examining the influence of climatic variables on raw Lyme disease cases, the influence of climatic variables on population–adjusted Lyme disease cases

(cases/100,000 people) has been done. Examining the graphs of cases adjusted by population with single climate variables reveals plots similar to the non–adjusted case plots, although the secondary peak in the JFM plots that represents the climate in the Upper Midwest endemic region is more evident (Figures A.9-A.16). Once again the peaks for the Upper Midwest and the Northeast come together in the AMJ plots, suggesting that climate in this three–month period represents a better link with the Lyme disease dynamics.

4.4.4 County Landuse Analysis Results using Raw Lyme Disease Cases

It has been speculated earlier in this paper and verified in the literature that more than one factor will affect the number of cases in the Lyme disease season as well as the county that will show high infection rates. The presence of deciduous woodlands, white-tailed deer and white–footed mice, and forest litter has been implicated (Anderson and Magnarelli 1980, Ostfeld et al. 1996, Frank et al. 1998, Dennis et al. 1998, Lindsay et al. 1999). Therefore, the landuse of a county may be directly related to that county's ability to support both the tick and host associated with this disease. The landuse characteristics of a county also affect the human population of a county, which is another necessary element of the transmission cycle. Because of its importance, the landuse of a sample of counties is investigated to discover the geographic makeup of counties associated with high and low Lyme disease reports.

The five highest Lyme disease counties (based on a yearly average for the six year period) were chosen and then compared to five selected counties that are in the same climate zone but have fewer than 20 average yearly cases. In other words five counties were selected that are in a favorable climate, in terms of precipitation, temperature, and surplus but have low reports of Lyme disease. Figures 21-28 reveal that there are a large number of counties with low Lyme disease counts that are in the “correct” climate zone for Lyme disease. Other factors are involved in introducing the disease to a region. Landuse (i.e., mostly rural or mostly urban) is one of the most obvious factors because of its link to the required elements of the transmission cycle.

The five counties with the highest average cases of Lyme disease include (from highest to lowest cases) Dutchess Co., NY (1261), Suffolk Co., NY (1161.33), Westchester Co., NY (691.83), Fairfield Co., CT (688.83), and Hunterdon Co., NJ (549.33). The five randomly selected counties with low average yearly reports include Rensselaer Co., NY (11.17), Greene Co., NY (15.25), Saratoga Co., NY (4.67), Richmond Co., NY (16.17), and Hudson Co., NJ (3.08). Examining each counties landuse characteristics reveals several possible explanations to why the five lower counties are indeed low, despite the fact that they have the same climate characteristics as the five highest counties. Landuse information was gathered from each state’s *DeLorme Atlas and Gazetteer*, 2000. All of the top five counties, except for Hunterdon County, are generally divided between highly populated urban areas with approximate populations between 266,809 and 1,379,690 and rural (forested) areas. Hunterdon County is predominately rural, which is unlike any of the other high report (endemic) counties.

The five counties with low average rates (<20) tend to have either dominantly urban or rural landuse with little to none of the other. Both Hudson and Richmond Counties are all urban with populations of 560,736 and 411,180 respectively; therefore, these counties may be unable to support either the tick or host populations necessary for the disease. Greene, Rensselaer, and Saratoga are highly rural areas with one or two smaller cities within them. Greene and Saratoga Counties both have large State Parks located in their boundaries with Greene County being dominated by the Catskill Park and the Adirondack Park occupying a fourth of Saratoga County. In examining these county's Lyme disease reports it makes sense that they have low reports even though they are in the "correct" climate as the highest Lyme disease cases because of their inability to support the tick and host populations because of either too much urban landuse or highly rural with few people available to contract the disease.

In comparing the landuse of the five highest counties in the Northeast to the five highest counties in the Upper Midwest, the five counties in the Upper Midwest are predominately rural with many small cities and a large number of small lakes and include Eau Claire County, WI (60.00), Washburn County, Hennepin County, MN (36.5), Ramsey County, MN (35.5), WI (26.5), and Chippewa County, WI (26.17), Although, Hennepin and Ramsey Counties, which are adjacent counties, contain the urban area, Minneapolis/St. Paul, with the rest of the county being rural. These findings are different than the landuse characteristics of the counties in the Northeast with the exception of Hennepin and Ramsey Counties. Although, when comparing these two areas, the numbers of reports of the two endemic areas are quite different with the Northeast county's average number of cases being between 500 and 1300 and the Upper Midwest county's average number of cases being only between 25 and 60. Therefore, it is not a surprise that their landuse characteristics are not identical given the huge difference in their average reports of Lyme disease.

4.4.5 County Landuse Analysis Results using Population–Adjusted Lyme Disease Cases

The noticeable change from the original plots of raw reports to the plots of cases adjusted by population is that the five highest Lyme disease counties have changed somewhat; therefore, these counties will be examined further. The five top counties for this analysis include (in order from highest to lowest cases) Nantucket County, MA (872.99), Dutchess County, NY (472.62), Hunterdon County, NJ (441.31), Washington County, RI (291.09), and Columbia County, NY (263.08). Obviously, these counties all have a large number of cases with respect to their population.

Since the climatic influence on Lyme disease cases was examined by population-adjusted cases, the landuse characteristics of these graphs will also be examined. The landuse characteristics of these counties are not similar to the top five counties aforementioned except that two counties, Dutchess and Hunterdon Counties, NY, are repeated. These counties tend to be more rural in nature with many small cities located within their boundaries with Dutchess County being the only county with a high amount of urban landuse. Likewise, the top five counties in the endemic region in the Upper Midwest are dominated by rural landuse and many small cities. Therefore, in light of these additional findings, the earlier speculation of a county needing an equal proportion of rural and urban may not hold true. This indicates that a more detailed analysis of a landuse effect is required in order to reach any firm conclusions.

It becomes obvious through this high versus low county comparison that the relationship between climate and Lyme disease reports is not a cause and effect relationship, but rather climate is an important "ingredient" in the transmission process. A county that cannot maintain or support the host, tick, or human populations will not be able to reach endemic status regardless of its climate. Climate plays an important role in this process of transmission of the disease because the range of climate variables (i.e., temperature, precipitation, and soil moisture surplus) places “constraints” on the system. Further research into the climate of a county and its Lyme disease numbers is needed, but the Lyme disease data must be available on a finer temporal scale (i.e., monthly county Lyme disease reports) than the annual totals that had to be used for this research.

4.4.6 Average “Climatic Envelope” Method Results

To more accurately quantify the range of precipitation, temperature, and surplus values that correspond to high cases of Lyme disease, a “climatic envelope” method was used. For this method, Lyme disease reports are plotted against two of the aforementioned climate variables (B.1-B.28). Unlike previous analysis, these plots are based on data by climate division with greater than five Lyme disease cases by year (non–adjusted). The climatic variables are based on the average value for the years 1994 to 1999 as reported in climate division climate data. An earlier trial of this envelope method produced plots with an excessive amount of clutter. The use of climate divisions makes the plots less cluttered (more smoothed) so that the climate ranges for various classifications of disease reports would be easier to interpret. Furthermore, anomalous regions became more evident. These plots were created for both JFM and AMJ time periods. Only two samples of the JFM plots are shown here (Figure 29 and 30) because it was determined in section 4.4.2 that the AMJ time period has a stronger relationship with Lyme disease.

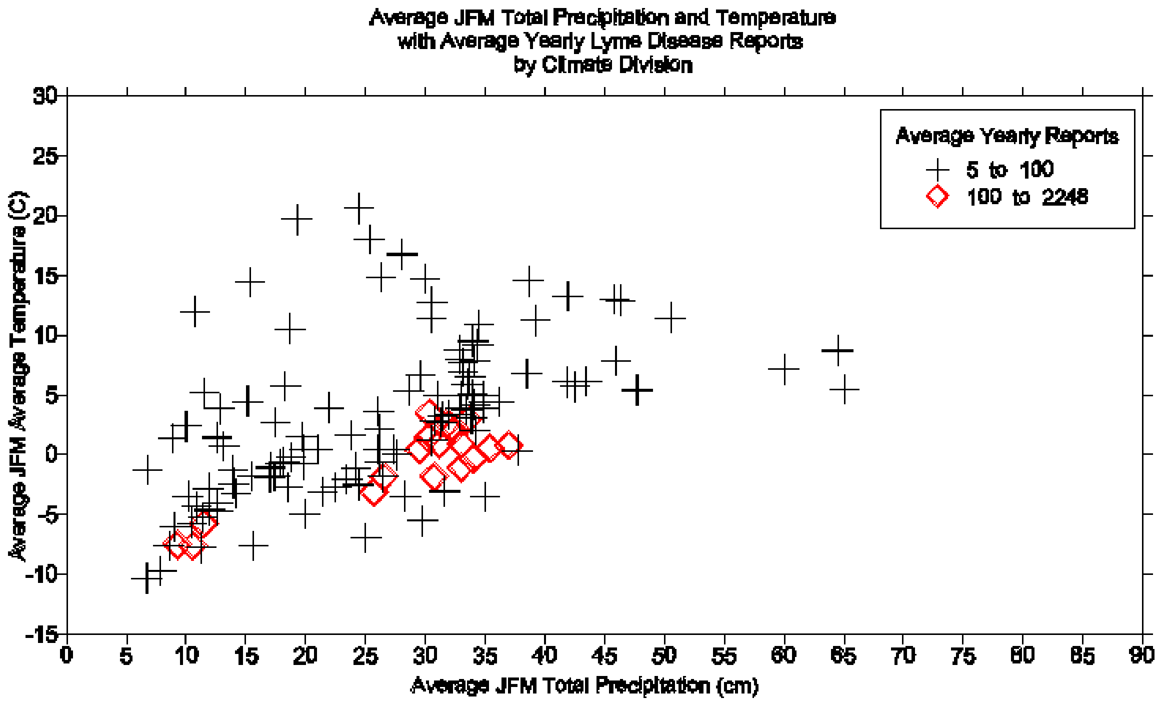

Figure 29: Graph of average JFM total precipitation and temperature values with corresponding average yearly reports (1994 to 1999) by climate division.

Figure 29 shows the average JFM precipitation totals of a climate division plotted against its mean temperature. The number of Lyme disease reports for each division is plotted by a symbol. In this case, the reports are split into two categories (5 to 100 and >100) to reduce clutter. In figure 29, the Upper Midwest endemic area is once again evident and corresponds to an average JFM temperature range from -8 to -6°C and an average JFM surplus value between 7.62 and 10.16 cm. Although not evident in the figures created, there is one outlier with a higher average JFM temperature (11°C) compared to the main cluster of cases and an average JFM surplus value (19.05 cm), which closely resembles the surplus values of the Upper Midwest. This outlier represents a climate division in Texas where Dallas/Ft. Worth is located and is not evident in these plots created because it did not meet these classifications. This climate division is important to examine, however, because of it unusually high number of average yearly cases (50.50) compared to the remaining climate divisions (0.82 to 15.42 average yearly cases). The main cluster of high case climate divisions is between -3 and 4°C for its average JFM temperature range and between 22.86 and 35.56 cm for its average precipitation range.

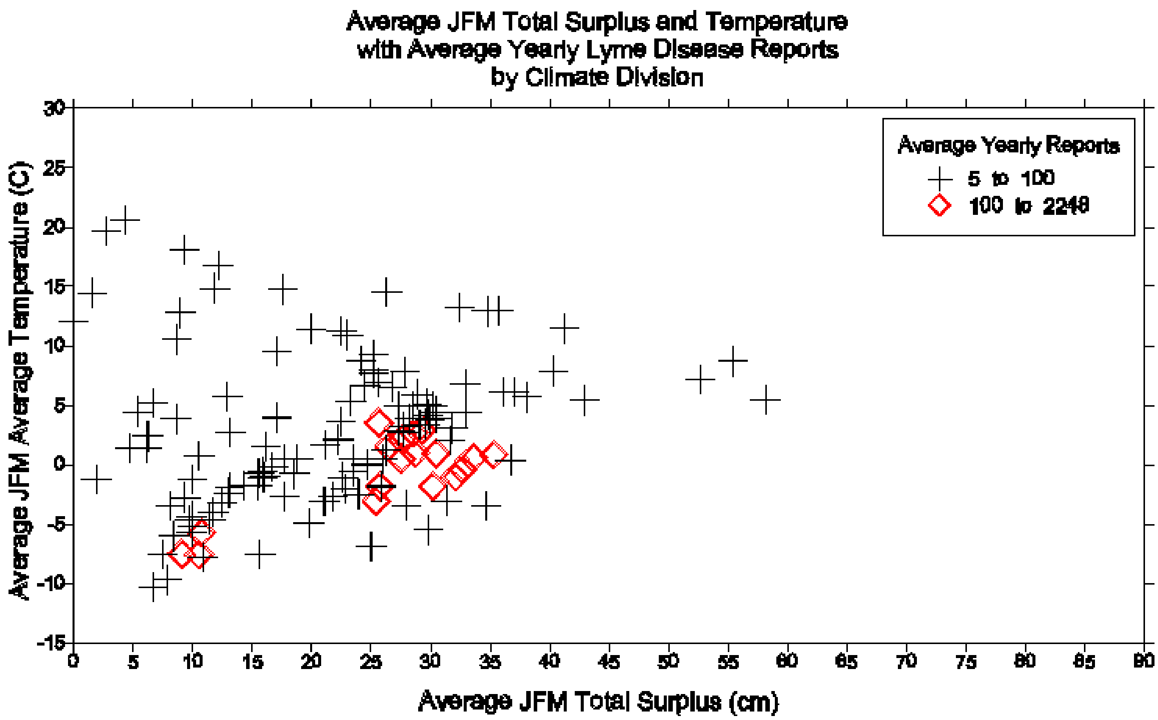

Figure 30: Graph of average JFM total soil moisture surplus and temperature values with corresponding average yearly reports (1994 to 1999) by climate division.

The same spatial pattern of the average JFM precipitation plot is seen in the average JFM surplus plot (Figure 30), with the secondary cluster of high case climate divisions visible and the aforementioned Texas climate division outlier still showing up as significant in the data. The average JFM surplus range for the Upper Midwest and the Texas outlier is between 7.62 and 10.16 cm, while the main cluster of high cases is between 25.43 and 35.33 cm, of course, the average JFM temperature range is the same as for the precipitation plot.

Analyzing the average AMJ precipitation and temperature plot (Figure 31) yields one main cluster of high cases. Interestingly, the Texas climate division outlier for the JFM time period shows up again for the AMJ time period. The main cluster shows an average AMJ temperature range of 12 to 18°C and an average AMJ precipitation range of 22.86 and 30.48 cm, whereas the outlier has a similar average precipitation value but a much higher average temperature value of approximately 22°C.

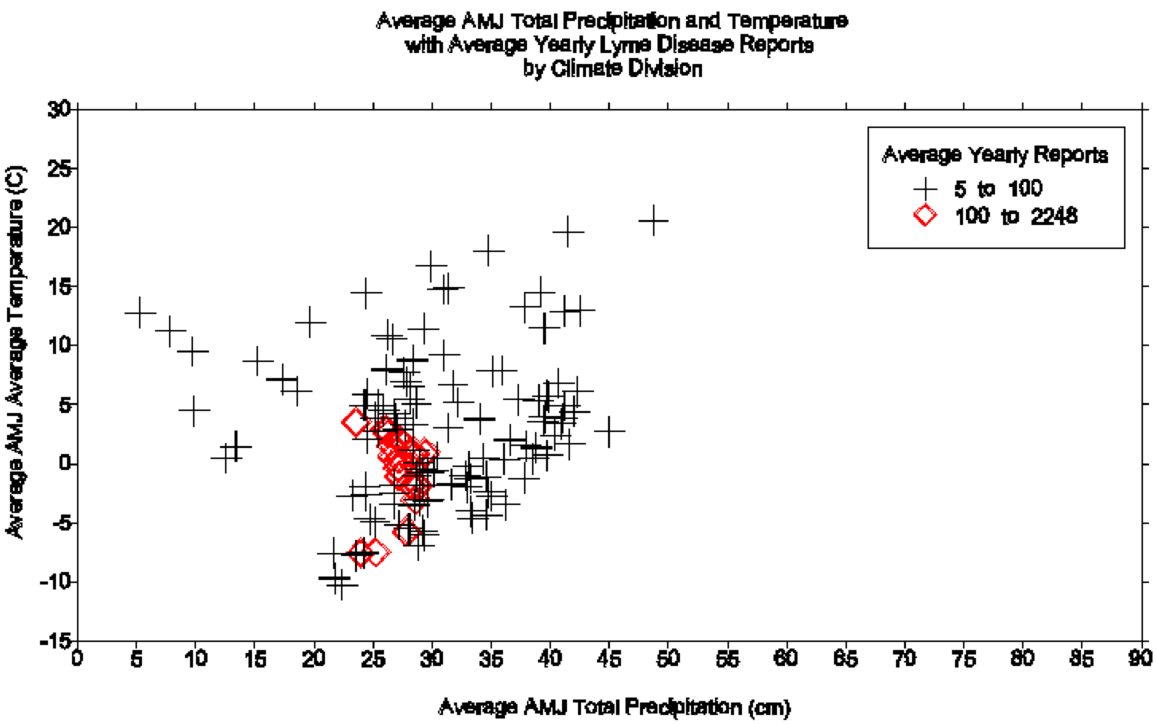

Figure 31: Graph of average AMJ total precipitation and temperature values with corresponding average yearly reports (1994 to 1999) by climate division.

The average AMJ surplus and temperature map (Figure 32) and data show a main cluster and one outlier similar to the average AMJ precipitation plot and data. The main cluster of high cases gives an average AMJ surplus range of between 5.08 and 11.43 cm with the outlier showing an average AMJ surplus value within that range, the temperature values are the same as for the average AMJ precipitation and temperature plots.

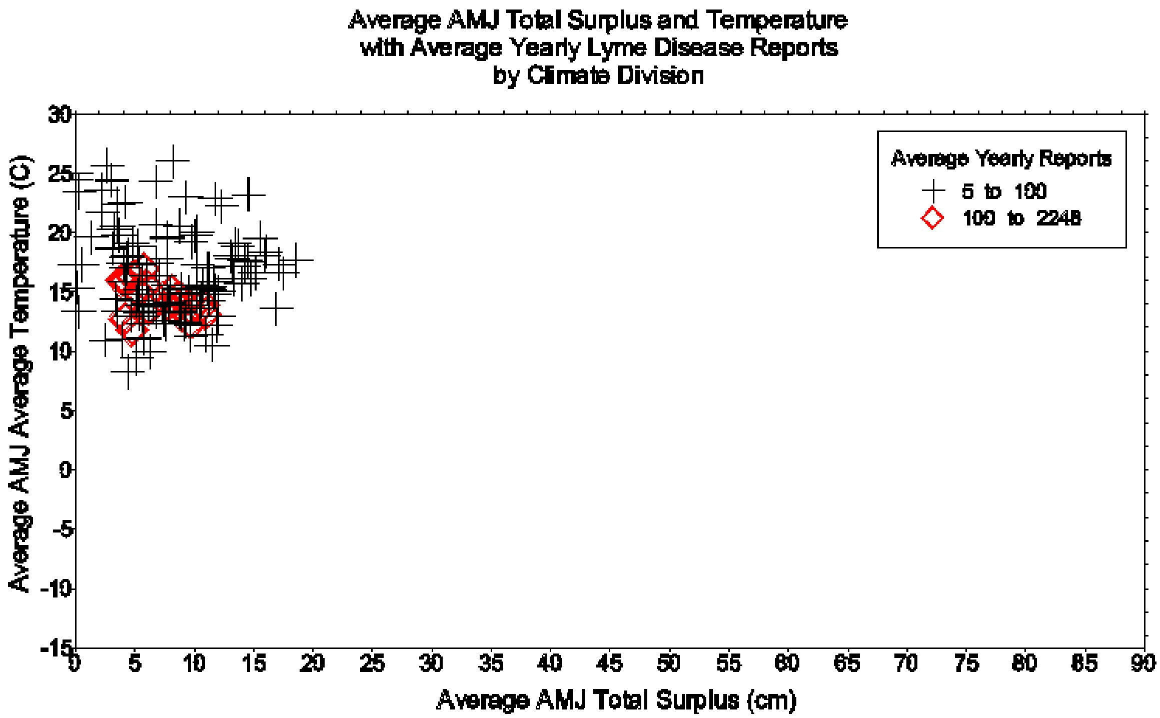

Figure 32: Graph of average AMJ total soil moisture surplus and temperature values with corresponding average yearly reports (1994 to 1999) by climate division.

One tentative conclusion that can be made from the envelope plots (Figures 31 and 32) is that precipitation in AMJ has a greater influence on the following season's Lyme disease reports than does surplus and temperature because of the tighter range of values for the this moisture variable. For all plots, the range of surplus and temperature values for the cluster of high cases is larger than the range of precipitation values compared to each variables total range of values for all cases. This tighter cluster shows that high reports of Lyme disease occur in climate divisions that for the most part have similar precipitation values. Regions that are too dry (precipitation < 23.61 cm) or too wet (precipitation > 29.42 cm) do not support reports greater that 100/year. Although, it must be restated that all elements of the disease must be present in the county in addition to the preferable climate in order for that county to be endemic with Lyme disease.

Due to the subjectivity of this tentative conclusion, the AMJ range of precipitation, surplus, and temperature for high average case (>100) climate divisions were calculated as a proportion of the total range of that variable. Unlike the above figures, the total range of the variable will be used for the calculations. Results show that for high average case divisions AMJ precipitation values span 12 percent of the total range of precipitation, AMJ surplus values span 33 percent, and AMJ temperature values span 22 percent. These calculations do support aforementioned speculations that precipitation in AMJ has a greater influence on the following Lyme disease season.

The climate division that brings about the most questions is the outlier climate division in Texas. This climate division has approximately the same precipitation and surplus values as the rest of the high case divisions, but has a much higher average temperature. This helps confirm the tentative conclusion that moisture variables are more influential in the Lyme disease transmission process than temperature variables.

In addition, these plots further lead to the conclusion that the AMJ time period is the more important and influential time period than the JFM period because of the absence of the secondary clustering of climatic variables for the Upper Midwest endemic region. The divisions come together to form one main cluster of high reports for Lyme disease. This envelope approach further suggests that the disease responds to the climate variables during the three–month period that directly prior to the overall peak season. The AMJ time period also corresponds to the peak nymphal activity, which is responsible for a large amount of the transmission of the disease to humans (Yuval and Spielman 1990, Shapiro and Gerber 2000).

This does not rule out the possibility of one or more important confounding effects. As the weather improves in the spring and early summer, the chance that the tick will attach itself to a human should increase greatly. It is possible that these results then an artifact of human behavior. Nevertheless, an infected tick must be present and must become attached to a person.

4.4.7 Yearly "Climatic Envelope" Method Results

The yearly (1994 to 1999) AMJ precipitation, surplus, and temperature plots (Figures B.5-B.16) show that the range of the climatic variable varies slightly from year–to–year, but are generally in one main cluster. This further suggests the conclusion that Lyme disease is constrained by geography and climate. The JFM yearly maps (Figures B.16-B.28) again show the secondary cluster associated with the lower precipitation, temperature, and surplus values of the Upper Midwest. Overall, the plots by year show that there is considerable yearly variability for the climatic variables and for disease reports.

Correlation–regression methods were attempted to find a relationship between climatic variables in a year and the disease reports in that year, but no clear patterns or connections could be found to explain the fluctuations that occur in the yearly Lyme disease reports.

4.4.8 Climate Envelope Model Results

A "climatic envelope" model was created to determine the range of climatic measures for counties in the middle 90th percentiles of the counties with ten or more cases per 100,000 people for the AMJ time period (Figures 33). The model is based upon upper and lower limits for precipitation, surplus, and average temperature as follows:

Predicted "favorable" climate = (AMJ Total Precipitation (cm) ≥ 23.57 or ≤ 33.45) + (AMJ Total Surplus (cm) ≥ 3.43 or ≤ 11.00) + (AMJ Average Temperature (°C) ≥ 10.99 or ≤ 17.93)

This model expands upon the results in sections 4.4.2 and 4.4.3 where average Lyme disease cases (raw and adjusted) were plotted against one climatic variable. Also the model expands upon the results of the average and yearly Lyme disease cases plotted against two climatic variables (section 4.4.6). It was found from these analyses that there is a clustering of the climatic variables associated with the endemic counties of Lyme disease. This model was created to take into account the clustering of climatic variables by only including counties that are in the range of high and low climatic values that are characteristic of the endemic zones.

A predictive map was created (Figure 33) which shows the counties that met the requirements outlined in the "climatic envelope" model. The map shows clearly the endemic regions, however, figure 33 also shows that there are counties such as those in southern Michigan, southeastern South Dakota, Nebraska, north–central Kansas, northern Oklahoma, northwestern Washington, Maine, southeastern Wisconsin, and northeastern Illinois that fall in the suitable climate range for Lyme disease to be present, but in actuality they have less than 10 reports/100,000 people. Likewise, there are counties such as those scattered in Missouri, Oklahoma, Texas, Tennessee, and Kentucky where the disease exists but their climate characteristics fall out of the 90 percent envelope. These counties that are not shown in the climate zone but do have reports of the disease, consequently, have only a small number of cases (ten) per 100,000 people. It is possible that in these counties with low rates of Lyme disease (but not shown in climatic envelope) the disease was not contracted in that county, but elsewhere, possibly in an endemic region.

Figure 33 shows that the most suitable climate for Lyme disease occurs in counties throughout the Northeast, Mid–Atlantic, Upper Midwest, and Central Plains and a few counties in Washington. Depending on whether these counties have established tick and host populations as well as sufficient human contacts will determine the ability of the county to reach endemic status. Many counties in the Northeast and Upper Midwest have established tick, deer and host populations and are in the suitable climate region. This explains the high rates of Lyme disease in these regions. The counties in the Central Plains and the state of Michigan are in the suitable climate region and have reported deer populations, but do not have established tick populations. This may account for the absence of the disease in these regions. The absence of ticks supporting Lyme disease in Central Plains could be because the area is dominated by heavy agriculture, which is not a suitable habitat for the tick to establish (Keirans et al. 1996). This map shows the counties that meet the climate requirements determined by the "climatic envelope" model that support high Lyme disease reports; therefore, for counties within the climate zone with little to no reports, the addition of the other necessary components could cause the disease to become a problem.

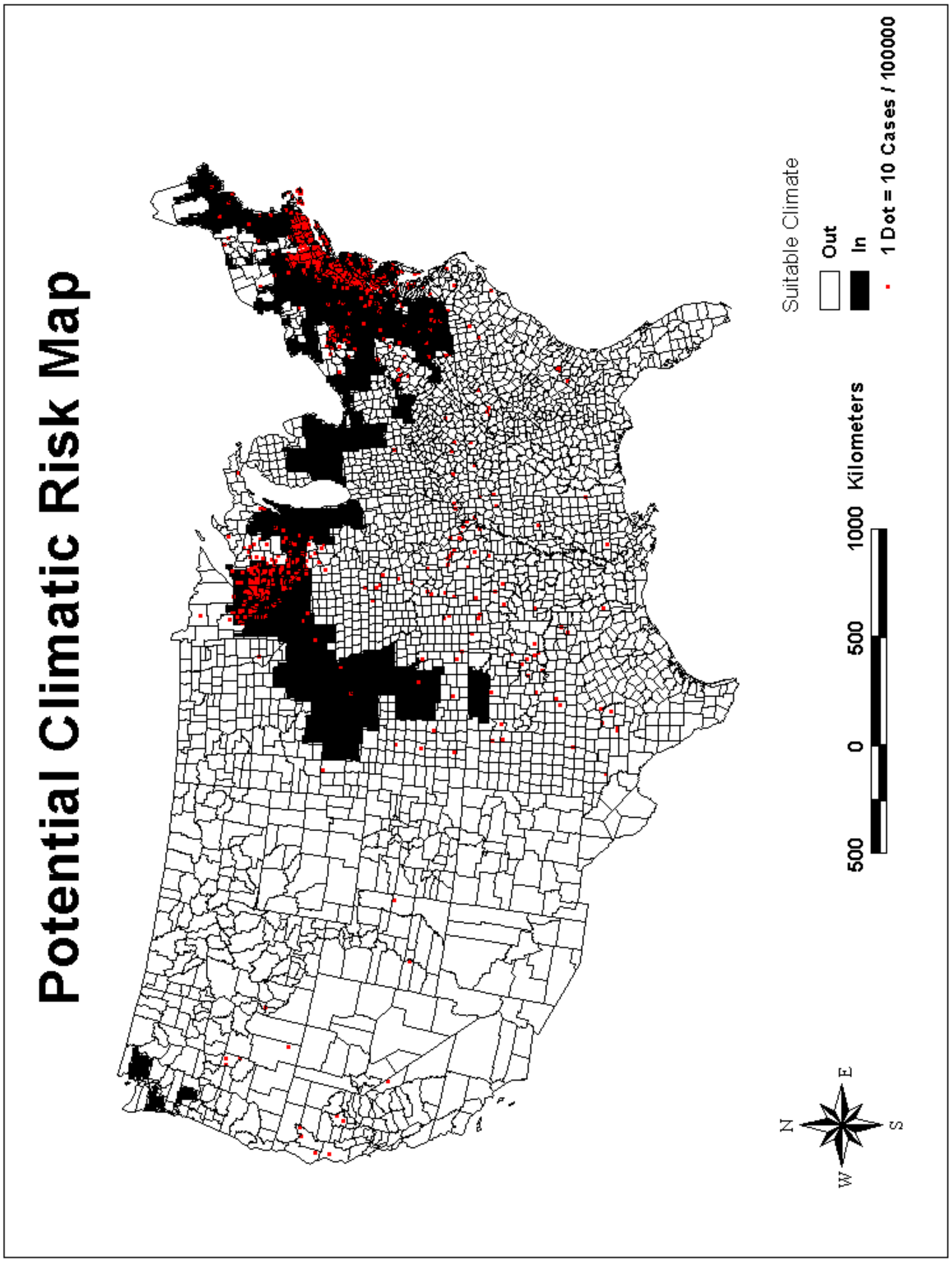

Figure 33: Potential Climatic Risk Map based on a “climatic envelope” model. This model is constrained by the average (1994 to 1999) AMJ total precipitation, AMJ average temperature, and AMJ total soil moisture surplus values of the middle 90 percent of counties with greater than 10 cases/100,000 people. Counties shaded in black are within the suitable climate range specified by the model.

CHAPTER 5. CONCLUSIONS

5.1 Overview

The overall goals of this research were to examine the seasonal distribution and annual variability of Lyme disease by state across the U.S. and to investigate the spatial distribution of the disease by focusing on the relationships among climate, landuse, and population and county Lyme disease reports. The spatial distribution of the disease shows a primary endemic region in the Northeast and a secondary region in the Upper Midwest. There is also a minor endemic area in the far west. The spatial cohesion of the disease suggests that it is controlled by geographic factors such as landuse/land cover, the population of tick, host, and humans, and climate. The seasonal distribution of Lyme disease has been found to be highly variable across the states of the U.S., although some regions show spatial cohesion. The trends of the disease also show considerable variability from state–to–state. This study focuses on county climate and to a lesser extent county landuse and population to discover any relationships that they may have on the spatial distribution of Lyme disease.

The lack of the appropriate data (i.e., Lyme disease reports by month by county) made it necessary to restrict analysis to broad temporal and spatial scales. Nevertheless, it was possible to find "hints" into the relationship among county climate, landuse, and population characteristics and Lyme disease. Unfortunately, no detailed predictive model could be formulated. The results found here should, however, prove to be beneficial for future research and should aid in formulation of prevention measures.

5.2 Conclusions

5.2.1 Seasonality of Lyme Disease

Past literature describes Lyme disease as being a summer disease in the eastern U.S., with its peak occurring during the months of June and July for the Northeast endemic area (WebMD Medical Library 22 March 2001, Gubler et al. 2001). It has also been found that the western U.S. generally reports incidences of Lyme disease from November through May with no peak month determined. It was hypothesized for this research that the month of August is also an especially important month with respect to Lyme disease outbreaks and that a secondary, lesser peak may occur in some states across the U.S. This study has found that for the years 1994 to 1999, the overall peak month for the U.S. occurs in August with July having only slightly fewer average cases. Furthermore, a secondary peak does occur, usually in December, but for only eight of the 48 contiguous states, which suggests that this disease is not restricted to the summer but can and does occur in the winter. Summer peaking states include most of the U.S. except for Arizona, Oklahoma, Minnesota, Arkansas, Texas, Louisiana, Florida, South Carolina, and Maine, which have a winter peak. The secondary, winter peak occurs in states such as California, Illinois, Maryland, Massachusetts, New York, and Pennsylvania, while Maine and Texas, show a secondary peak in the summer. These two peaks can be explained by the presence and activity of the tick vectors and the potential contact with humans. The nymphal tick is active during the summer when human outdoor activity is at its highest, thereby, explaining the maximum peak in the summer months. Whereas, the winter peak can be explained, in part, by the heightened activity of the adult tick during the cold season of each year. Lyme disease is predominately a summer–time disease, although during winter the aforementioned regions should take precautions.

5.2.2 Trend of Lyme Disease

Lyme disease has also been reported to be infecting an increasing number of people each year across the U.S. (Gratz 1999). It was hypothesized that not all states would follow this overall trend in reports but that many may be experiencing no apparent change or may show high yearly variability. It is concluded that indeed many states exhibit a high amount of yearly variability of the disease over the ten–year period with no apparent increasing or decreasing trend. Only 11 states have in fact been increasing in reports and are predominately located in the Northeast, where reported cases are highest. On the other hand, there are two states, Missouri and Wyoming that show a decreasing trend with one (Missouri) being located in the central U.S. and the other in the western U.S. Although statistically decreasing, Wyoming's Lyme disease reports are low each year, whereas, Missouri has declined from a high of approximately 200 cases in 1991 to around 50 cases in 2000. A large portion of states located in the west with very low Lyme disease counts have no apparent change in their number of reports over the ten years. In general, from the years 1991 to 2000, the data shows that Lyme disease is an increasing threat to the U.S. especially in endemic regions.

5.2.2 Population Influence on Lyme Disease

Results show that there is a relationship between population of a county and the raw number of Lyme disease reports in a county. Initially it appeared that as population/population density increased, Lyme disease reports decreased, but further analysis using a smaller sample of counties shows that a wide range of county populations/population densities can support high numbers of Lyme disease cases. Nevertheless, it appears that there may be a population/population density that is too high to support the disease because of a lack of suitable forested habitat, and one that is too low. It is concluded that too high a population of a county reduces the possibility for a sufficient host–vector system and too low a population removes the possibility for sufficient human contacts.

5.2.3 Climatic Influence on Lyme Disease (One and Two Variable Analyses)

The influence of climate on Lyme disease has been limited in past research, although it has been established that there is some connection between climate and the vectors of Lyme disease. Using Lyme disease cases as a surrogate to tick density data and tick–human contacts, this study has begun to uncover some "hints" into this climate-disease link. First and foremost, this research shows that the climate and Lyme disease relationship is not a direct cause–and–effect relationship, but instead, the climate associated with the months directly preceding the upcoming Lyme disease season may have a control on the outcome of the Lyme disease season. Moreover, it is suspected that there is a core climate zone that is most "favorable" for the spread of the disease.

This research proposes that the climate during the three–month time period of April, May, June (AMJ) may have some degree of influence on Lyme disease the following summer. AMJ is concluded to be the better of the two time periods examined because the plots of Lyme disease reports and the climate variables all show that there is only one core region of climatic values in which the disease occurs. Whereas, the JFM plots show a secondary peak climatic zone where high rates of Lyme disease also occur.

Furthermore, it has been found that moisture variables (i.e., total precipitation and total soil moisture surplus) seem to have more of a control on Lyme disease than temperature.

The figures of Lyme disease cases by climate division (shown by symbols) plotted with two climate variables (i.e., precipitation/surplus and temperature values) in addition to the proportions of that were calculated show that for climate divisions with high cases there is a smaller range of values for precipitation than the temperature and surplus variables.

5.2.4 Landuse Analysis

An attempt was made to analyze the landuse of counties with high Lyme disease totals and rates and those of low disease totals and rates to see whether there is a dominant landuse pattern that is associated with endemic counties. From this analysis, it was difficult to conclude which landuse characteristics are representative of endemic Lyme disease counties. It is assumed that the county must have a sufficient amount of both rural and urban areas so that the tick–host–human transmission cycle can be completed. Suburban forested area may well have the greatest potential for human–tick contacts. The literature does highlight the importance of woodland forests and sufficient leaf litter in order for the tick population to be established and grow (Dennis et al. 1998, Lindsay et al. 1999).

5.2.4 Climatic Envelope Model

Lastly, the "climatic envelope" model combines the variables so that places with the "favorable" climatic conditions for the disease could be identified. Within these regions, the disease can occur only if all the required components are established. This means that a county must have an established and sufficient population of tick, deer, and humans as well as the suitable climate for the disease to become problematic. Obviously, there is a need for further detailed research into this climate–disease link to determine the degree to which climate and weather affects the Lyme disease season.

5.3 Future Research and Recommendations

An obvious dilemma for this research is that the optimal data needed to research the climate–disease links was not attainable: therefore, a conclusive predictive model of this relationship could not be formed. Since this research was forced to use yearly Lyme disease reports per county for all states of the contiguous U.S. only the start of a full investigation into the climatic controls into Lyme disease was accomplished. It is recommended for future research that monthly reports per county be analyzed against monthly climatic variables. Then it would be conceivable to find the exact month(s) that enters into Lyme disease as well as the degree to which that month's climate controls the upcoming Lyme disease season.

It is recommended that the three–month period of April, May, and June is the most suitable place to start any further investigations into the climate–disease link. An emphasis should be placed on the moisture characteristics of the county. Literature has also highlighted the microclimate of the vector's habitat (i.e., leaf litter); therefore, future researchers may want to investigate the microscale climate of the tick's habitat (i.e., ground temperature, leaf litter moisture) and/or the microscale climate of the host's habitat. Lastly, examining the landuse characteristics of counties (i.e., percent woodlands, closeness of homes to woodlands, percent urban) with high rates of Lyme disease is recommended. Ultimately, an investigation that pulls all the required elements together may be the most efficient way to discover what causes an area to become endemic with Lyme disease because of the complexity associated with transmitting this disease.

5.4 Summary of Conclusions

1) The seasonality of Lyme disease is more variable across the U.S. than previously reported. For much of the U.S., the peak occurs in July and August, but some states (Arizona, Oklahoma, Minnesota, Arkansas, Texas, Louisiana, Florida, South Carolina, and Maine) have their peak in the winter. Although, Lyme disease is considered to be mostly a summer disease, results here show a secondary seasonal peak in December for six of the 48 contiguous states (California, Illinois, Maryland, Massachusetts, New York, and Pennsylvania).
2) The disease has been reported to be on a general rise for the entire U.S. (Keirans et al 1996), but only 11 states show a statistically significant increasing trend from 1991 to 2000. Most states have great year–to–year variability. The increasing states are generally located in the Northeast and include Connecticut, Minnesota, Maine, Maryland, Massachusetts, New Jersey, Pennsylvania, Rhode Island, and Vermont. Florida and Oregon are increasing but are located outside the endemic regions of the Northeast and Upper Midwest. Wyoming and Missouri are the only two states show that they are decreasing in Lyme disease reports, while the 35 remaining states show either no trend or having an insufficient amount of reports. Regardless, these finding support previous accounts that the disease is increasing.

3) The population/population density of a county does apparently influence the number of reports (raw) for that county, and the data suggest that there is a population/population density that is too high and too low to support the high reports of the disease.
4) Findings show that climate does have a relationship with the geography of Lyme disease, although this research shows only general relationships. It is concluded that the three–months (AMJ) that precede the general peak of Lyme disease in July and August may be the “effective” climate of the host–vector system. Certainly, future research into the climate–disease link should examine the weather–disease logs.
5) The graphs of the two climatic variables plotted against average and yearly Lyme disease show that moisture variables (i.e., precipitation and soil moisture surplus) have more of an influence on the Lyme disease season than does temperature.
6) The “climatic envelope” method showed that climate divisions with 100 or more average cases per year have a lower limit and upper limit of 3.97 and 11.02 cm for their average AMJ surplus values, a lower limit and upper limit of 23.61 and 29.42 cm for their average AMJ precipitation values, and a lower limit and upper limit of 11.80 and 16.82°C for their average AMJ temperature values.
7) Results from the “climatic envelope” model show that the “favorable” climate for Lyme disease to occur in, if all elements are present, includes counties with an average AMJ precipitation range from 23.57 to 33.45 cm, an average AMJ surplus range from 3.43 to 11.00 cm, and an average AMJ temperature range from 10.99 and 17.92°C.

8) The potential climatic risk map shows the areas where the climate meets the requirements specified by the "climatic envelope" model. Mostly the disease occurs within this range of values, although there are some counties where the disease has been reported but is not the suitable climatic zone shown by the map. Other counties show that they are included in the suitable climatic zone but do not have any reports of the disease. This potential climatic risk map only shows were the climate is "correct"; all other elements (i.e., tick, host, and human contacts) must be present in order for the disease to be endemic.

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APPENDIX A

AVERAGE LYME DISEASE CASES (RAW AND ADJUSTED) PLOTTED AGAINST JFM/AMJ CLIMATIC VARIABLES

This appendix contains the graphs of average Lyme disease cases by county (raw and adjusted) plotted against climate division JFM/AMJ climatic variables not included in Chapter 4. Those graphs that are shown in Chapter 4 include average cases plotted against average JFM precipitation, temperature, surplus, and deficit (Figures 21-24) and average cases plotted against average AMJ precipitation, temperature, surplus, and deficit (Figures 25-28).

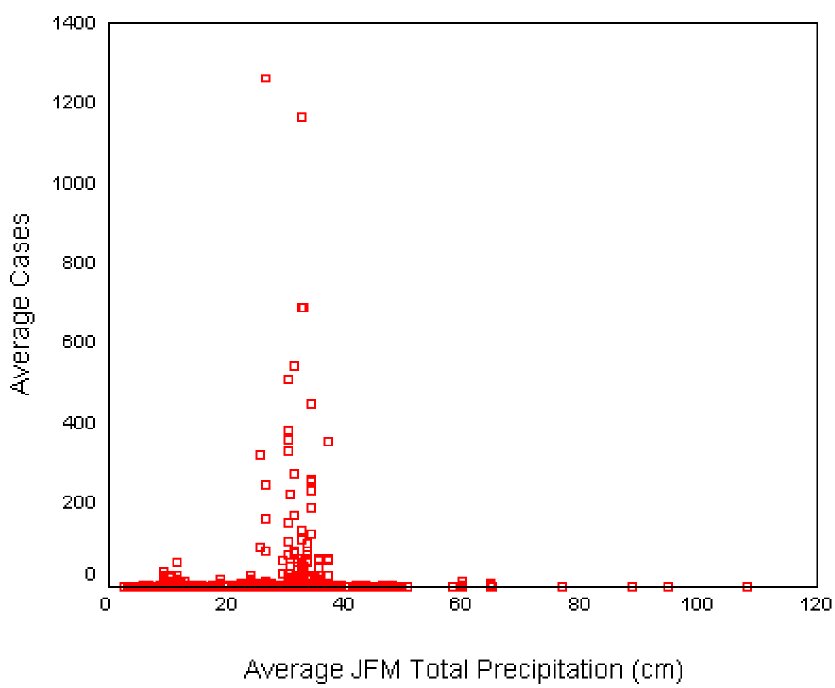

Figure A.1: Plot of average cases by county with corresponding average JFM precipitation values based on data from 1994 to 1999.

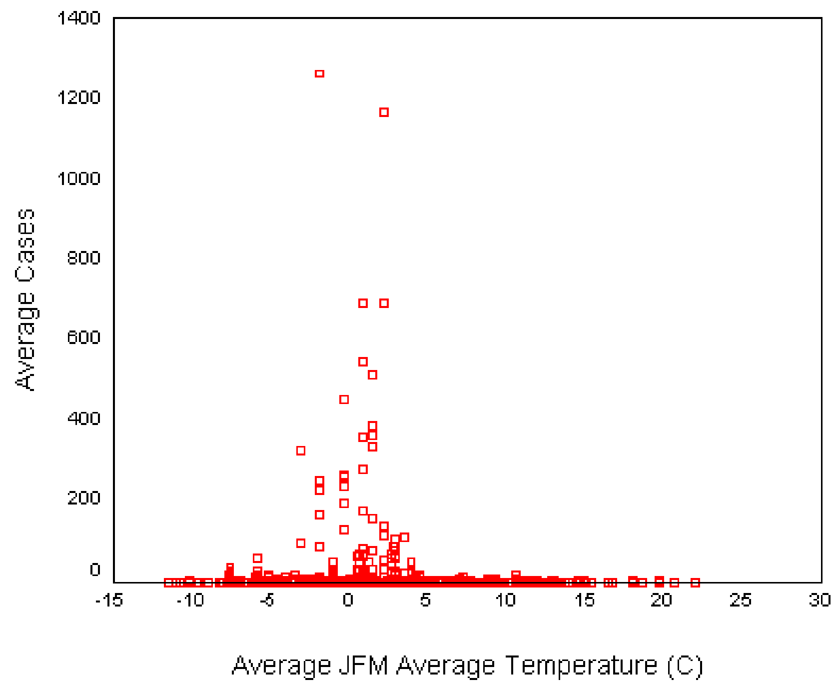

Figure A.2: Plot of average cases by county with corresponding average JFM temperature values based on data from 1994 to 1999.

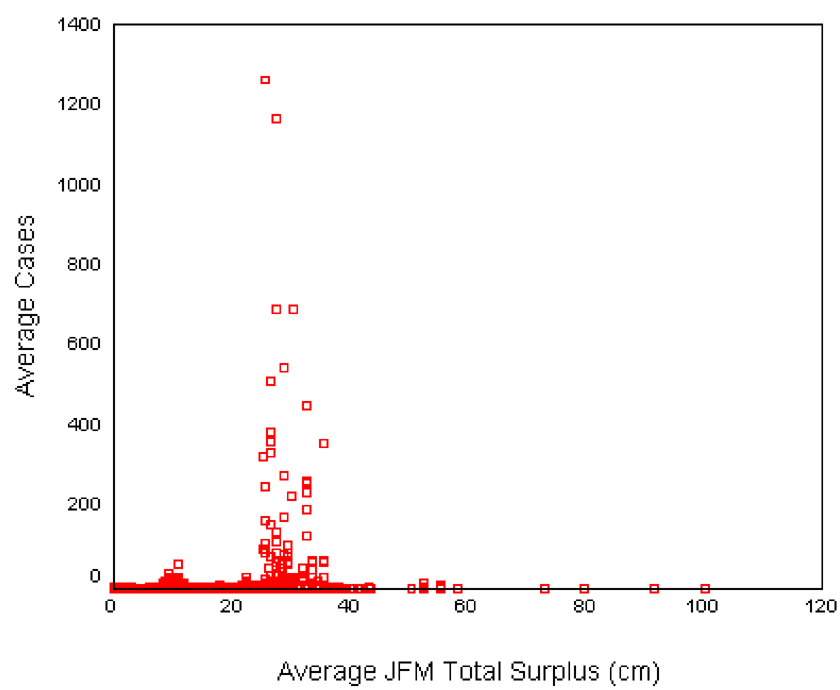

Figure A.3: Plots of average cases by county with corresponding average JFM soil moisture surplus values based on data from 1994 to 1999.

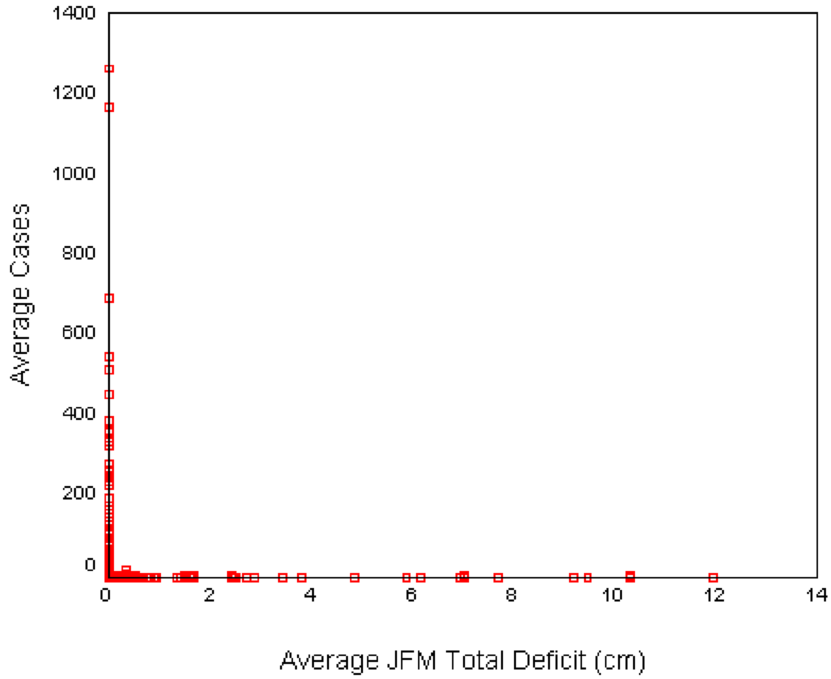

Figure A.4: Plot of average cases by county with corresponding average JFM soil moisture deficit values based on data from 1994 to 1999.

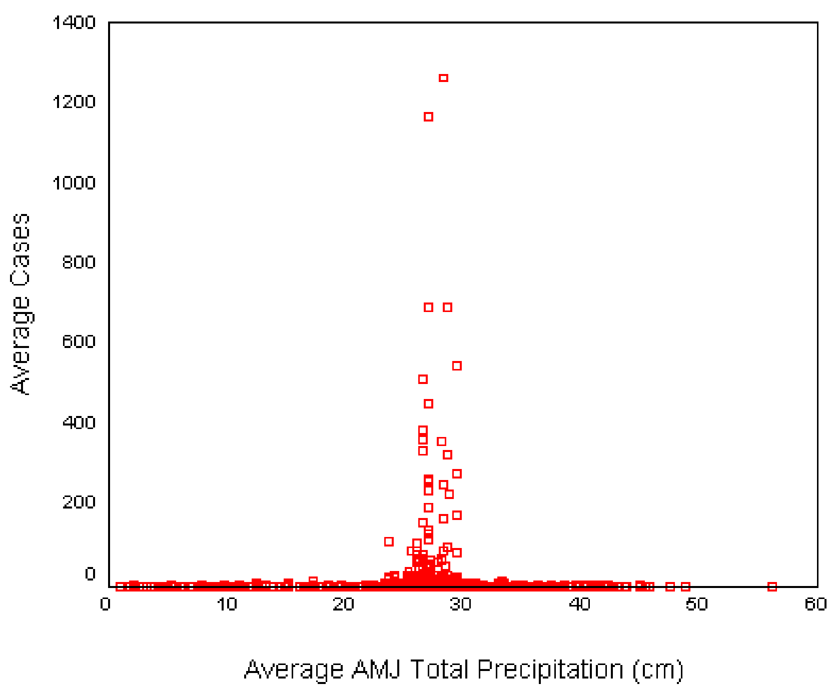

Figure A.5: Plot of average cases by county with corresponding average AMJ temperature values based on data from 1994 to 1999.

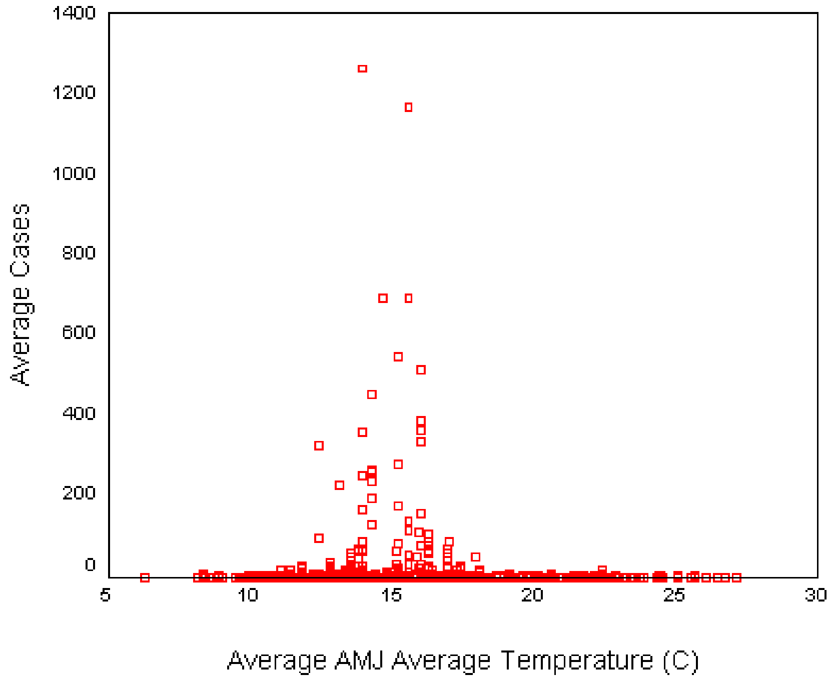

Figure A.6: Plot of average cases by county with corresponding average AMJ temperature values based on data from 1994 to 1999.

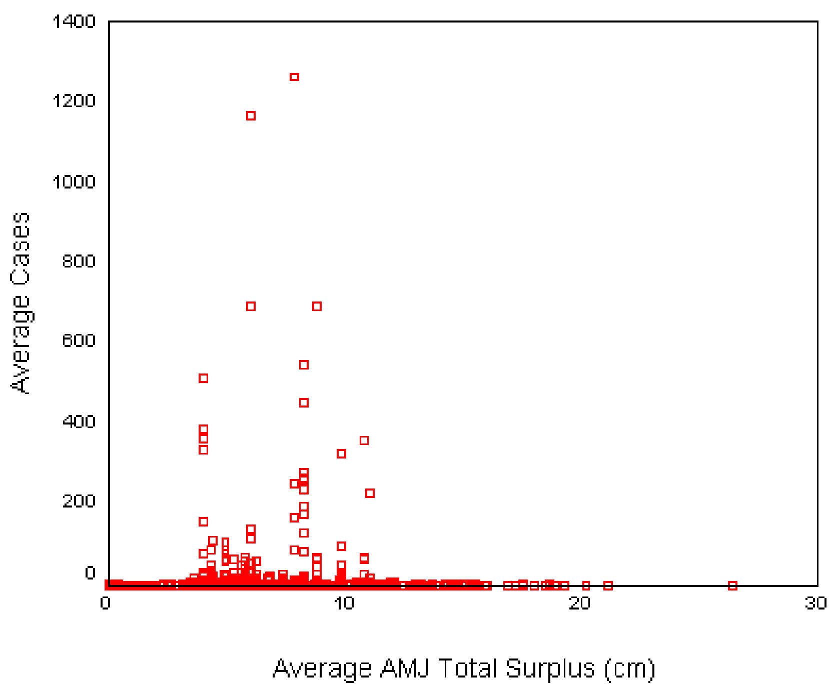

Figure A.7: Plot of average cases by county with corresponding average AMJ soil moisture surplus values based on data from 1994 to 1999.

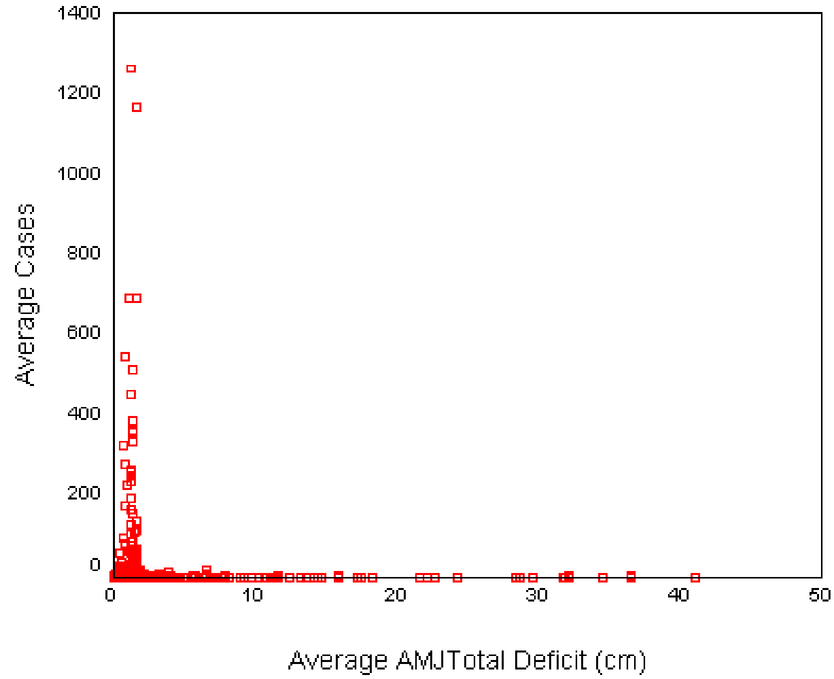

Figure A.8: Plot of average cases by county with corresponding average AMJ soil moisture deficit values based on data from 1994 to 1999.

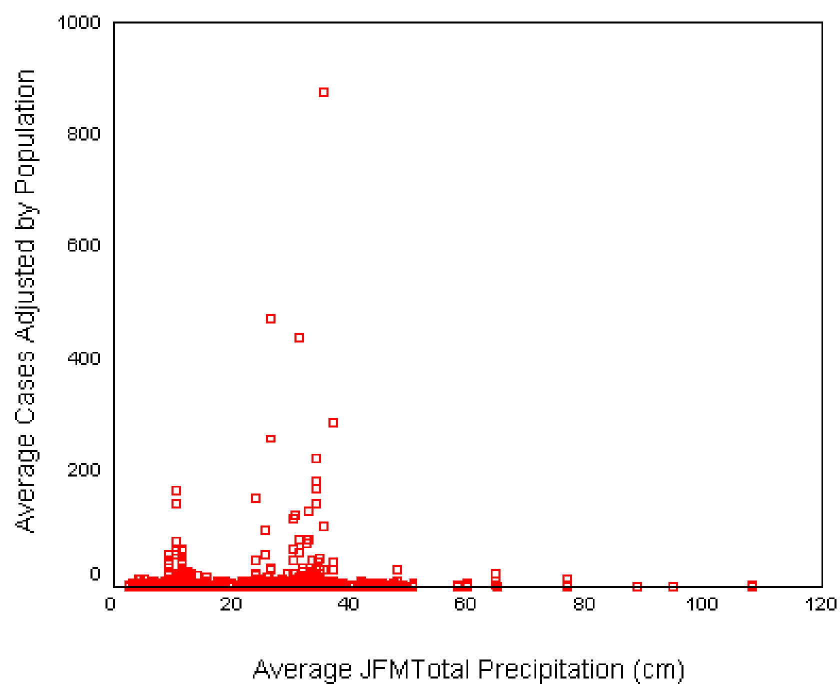

Figure A.9: Plot of average cases adjusted by population by county with corresponding average JFM precipitation values based on data from 1994 to 1999.

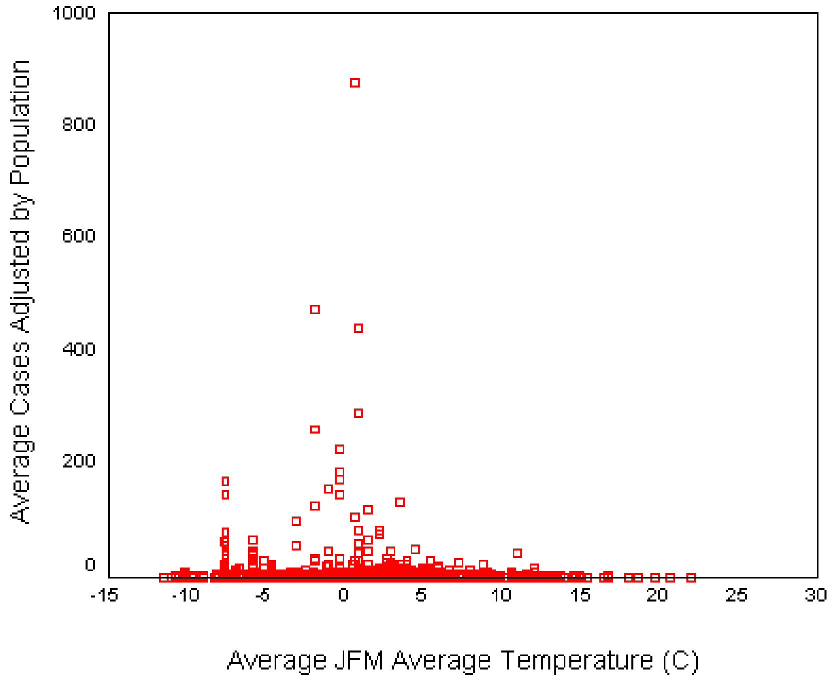

Figure A.10: Plot of average cases adjusted by population by county with corresponding average JFM temperature values based on data from 1994 to 1999.

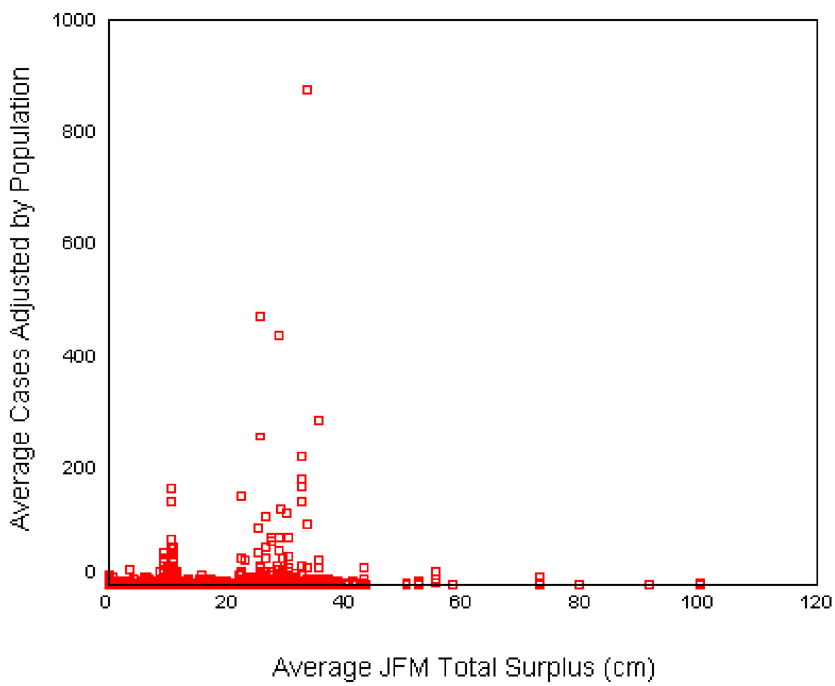

Figure A.11: Plot of average cases adjusted by population by county with corresponding average JFM soil moisture surplus values based on data from 1994 to 1999.

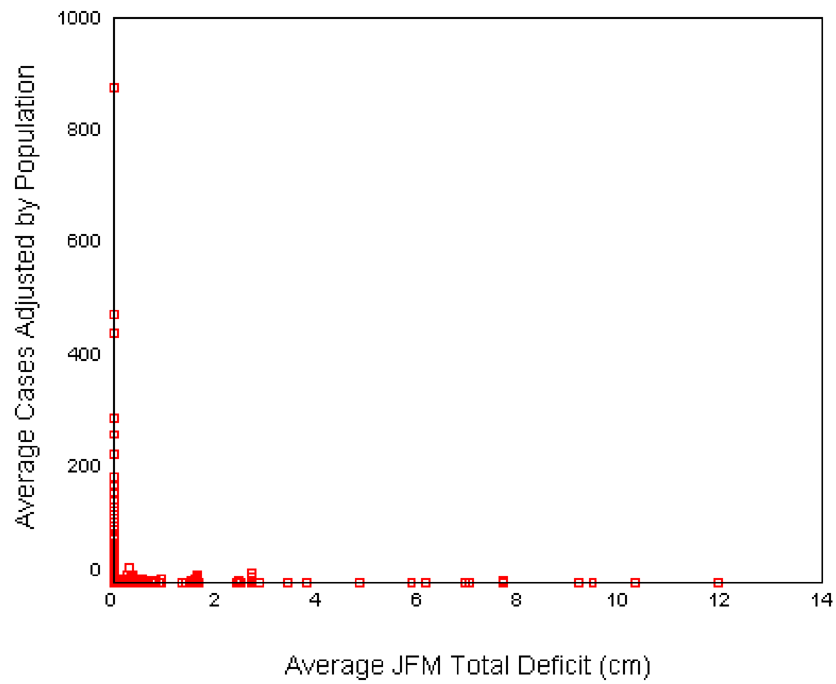

Figure A.12: Plot of average cases adjusted by population by county with corresponding average JFM soil moisture deficit values based on data from 1994 to 1999.

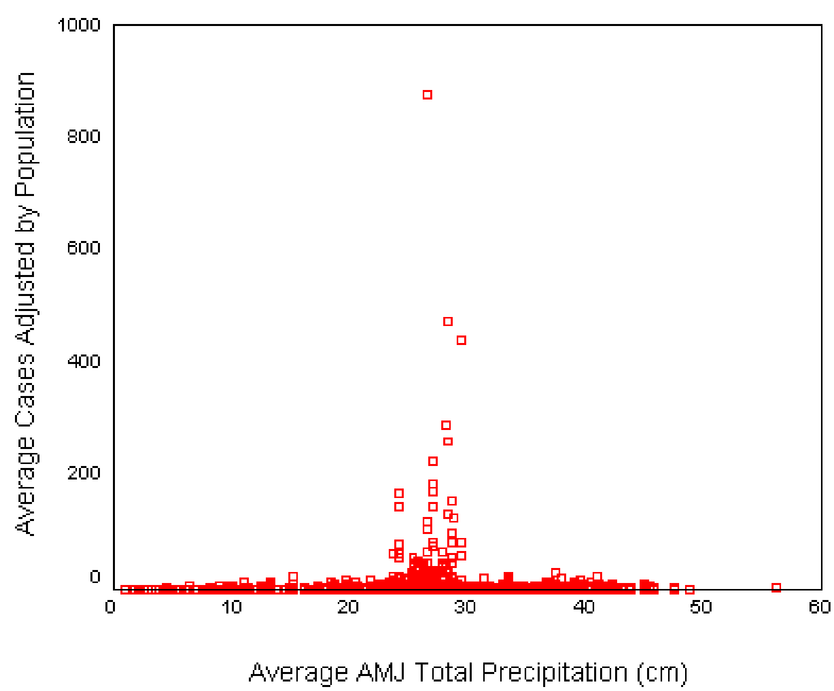

Figure A.13: Plot of average cases adjusted by population by county with corresponding average AMJ precipitation values based on data from 1994 to 1999.

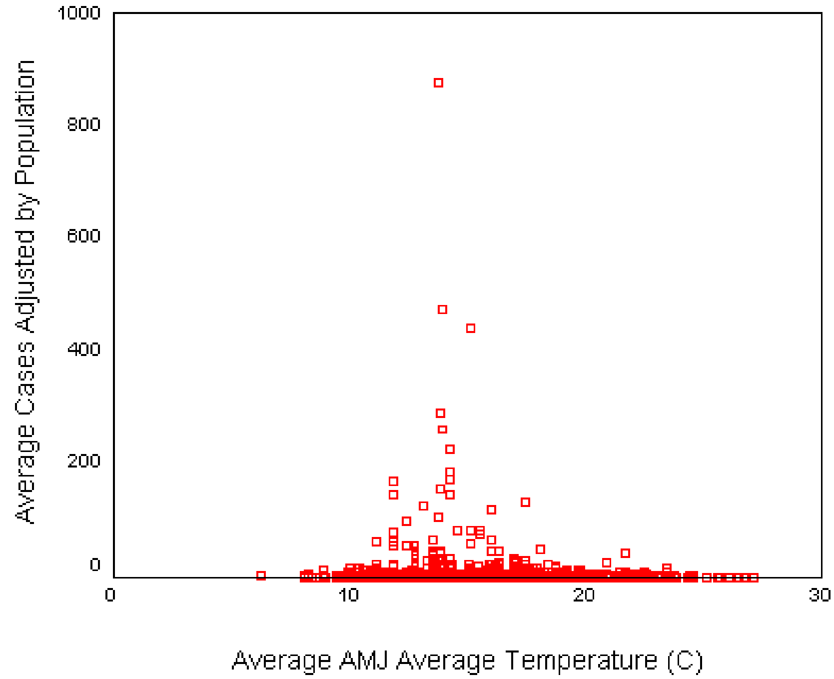

Figure A.14: Plot of average cases adjusted by population by county with corresponding average AMJ temperature values based on data from 1994 to 1999.

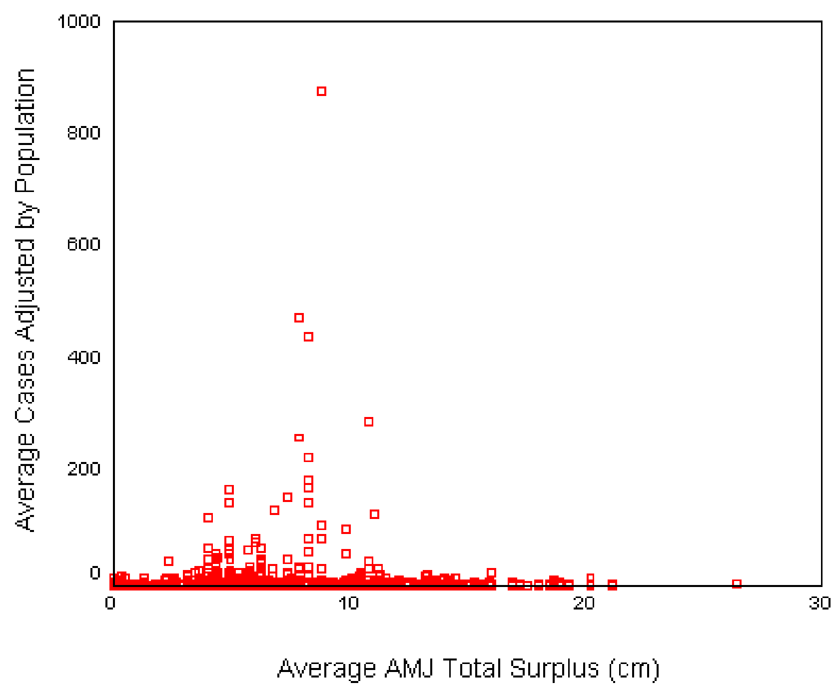

Figure A.15: Plot of average cases adjusted by population by county with corresponding average AMJ soil moisture surplus values based on data from 1994 to 1999.

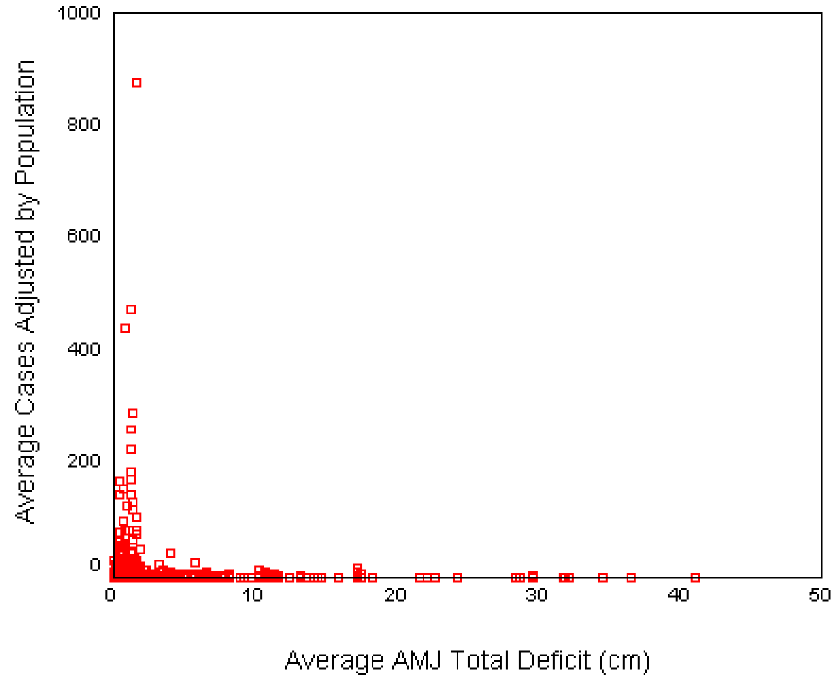

Figure A.15: Plot of average cases adjusted by population by county with corresponding average AMJ soil moisture deficit values based on data from 1994 to 1999.

APPENDIX B

SURFER CREATED GRAPHS OF AVERAGE AND YEALRY LYME DISEASE REPORTS PLOTTED AGAINST TWO CLIMATIC VARIABLES

This appendix contains the graphs of average and yearly Lyme disease reports plotted against 2 climatic variables of both the JFM and AMJ time periods (total precipitation against average temperature or total surplus against average temperature) not included in Chapter 4. Those graphs that are shown in Chapter 4 include the Average Yearly Lyme disease reports graphed against both the total precipitation and average temperature (JFM and AMJ) and total surplus and average temperature (JFM and AMJ).

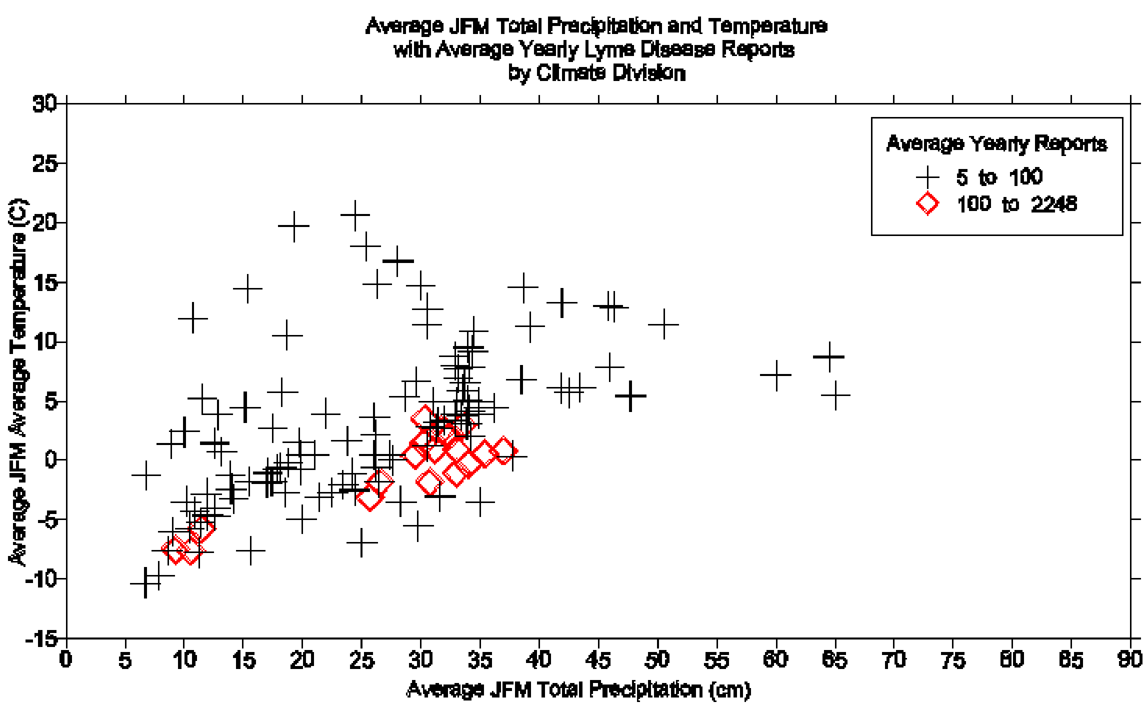

Figure B.1: Graph of average JFM total precipitation and temperature values with corresponding average yearly reports (1994 to 1999) by climate division.

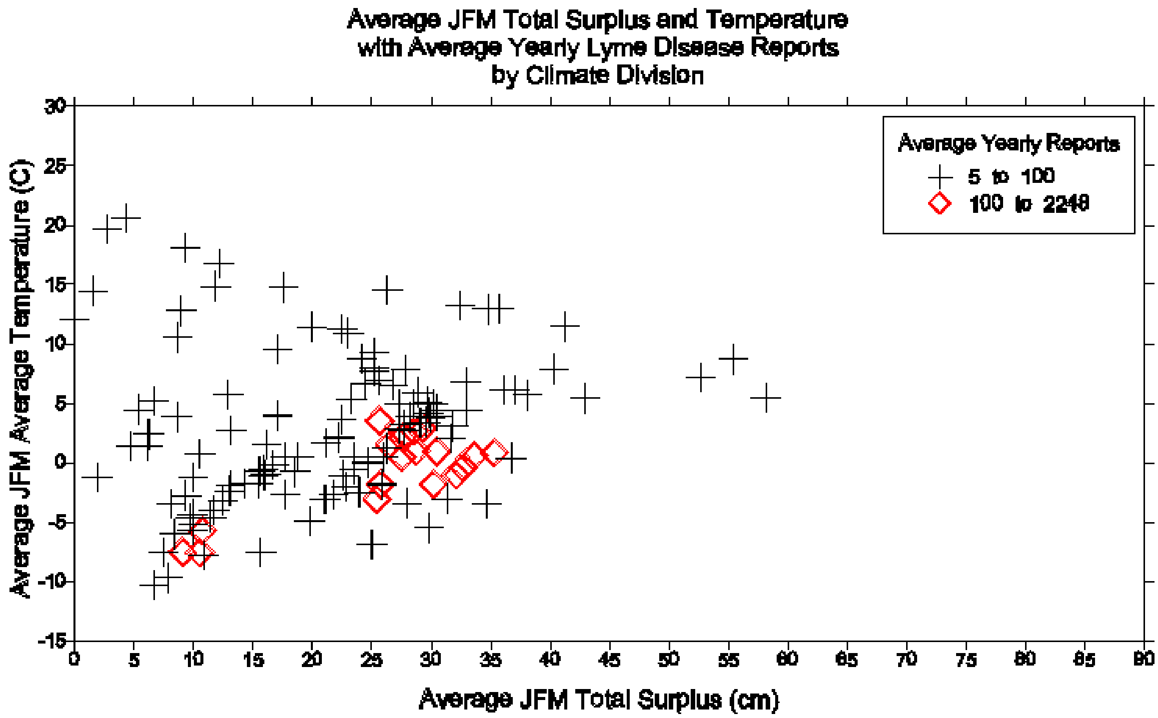

Figure B.2: Graph of average JFM total soil moisture surplus and temperature values with corresponding average yearly reports (1994 to 1999) by climate division.

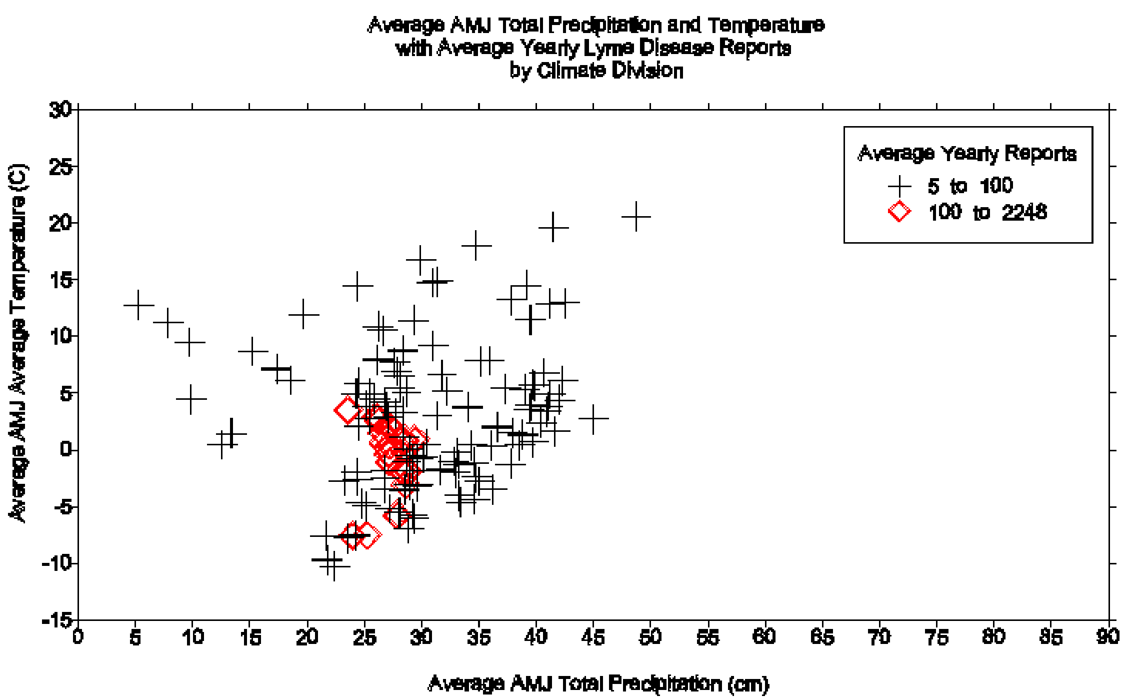

Figure B.3: Graph of average AMJ total precipitation and temperature values with corresponding average yearly reports (1994 to 1999) by climate division.

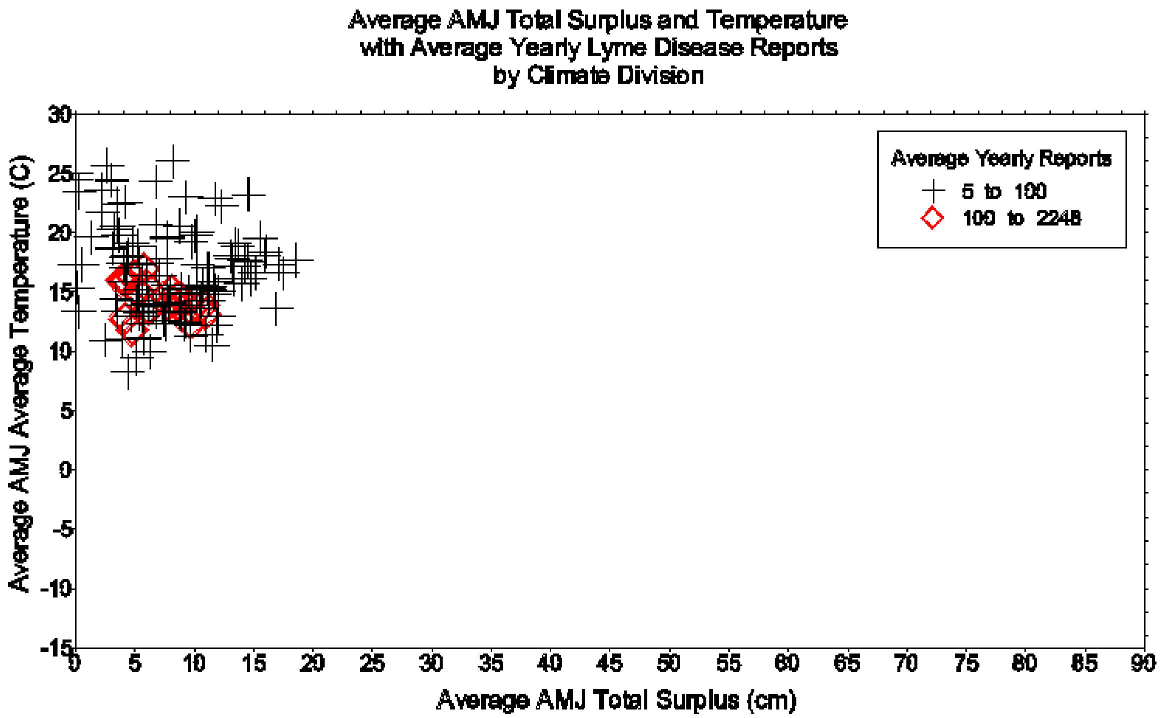

Figure B.4: Graph of average AMJ total soil moisture surplus and temperature values with corresponding average yearly reports (1994 to 1999) by climate division.

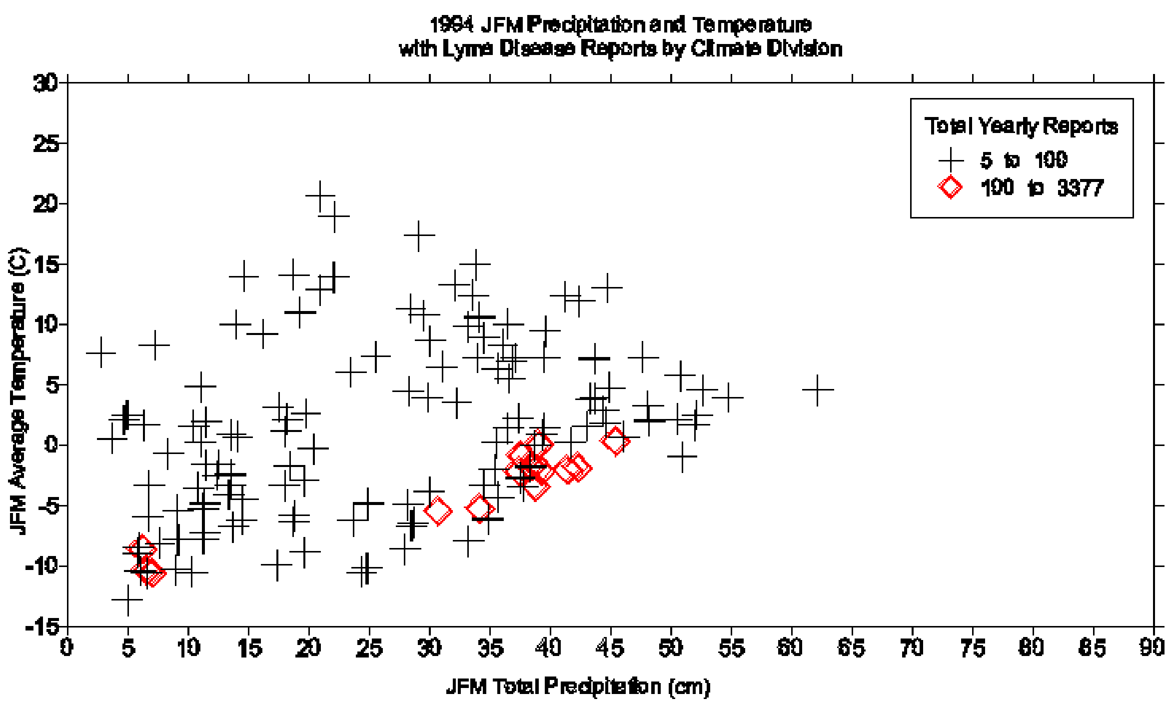

Figure B.5: Graph of 1994 JFM precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

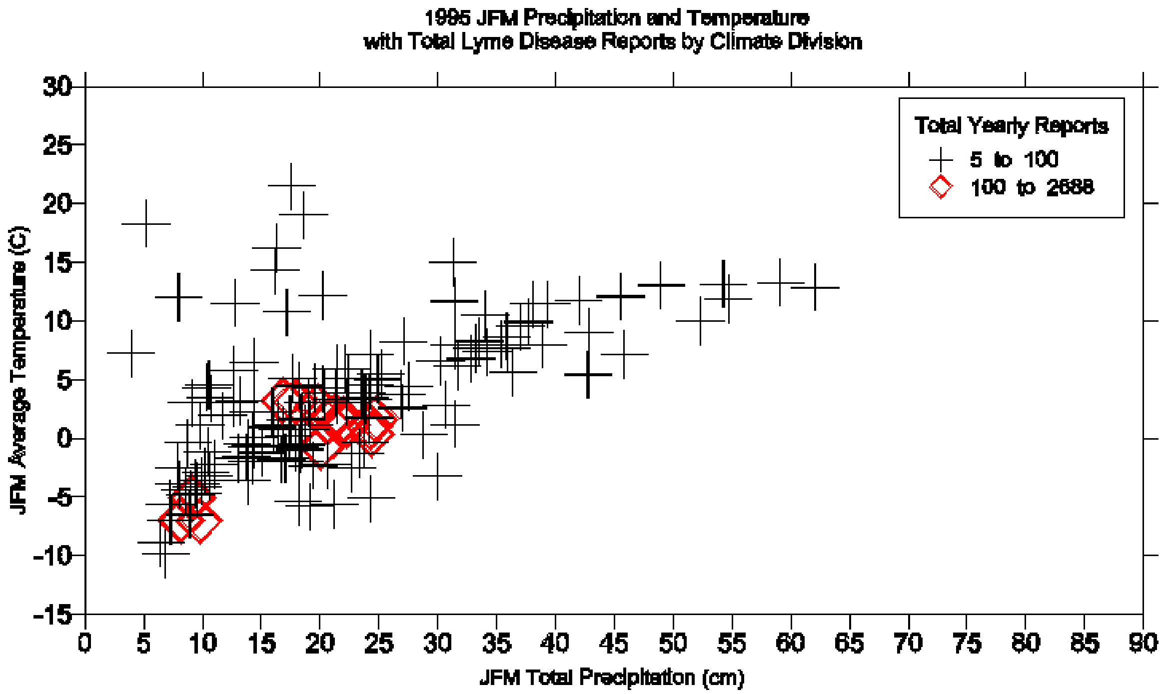

Figure B.6: Graph of 1995 JFM precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

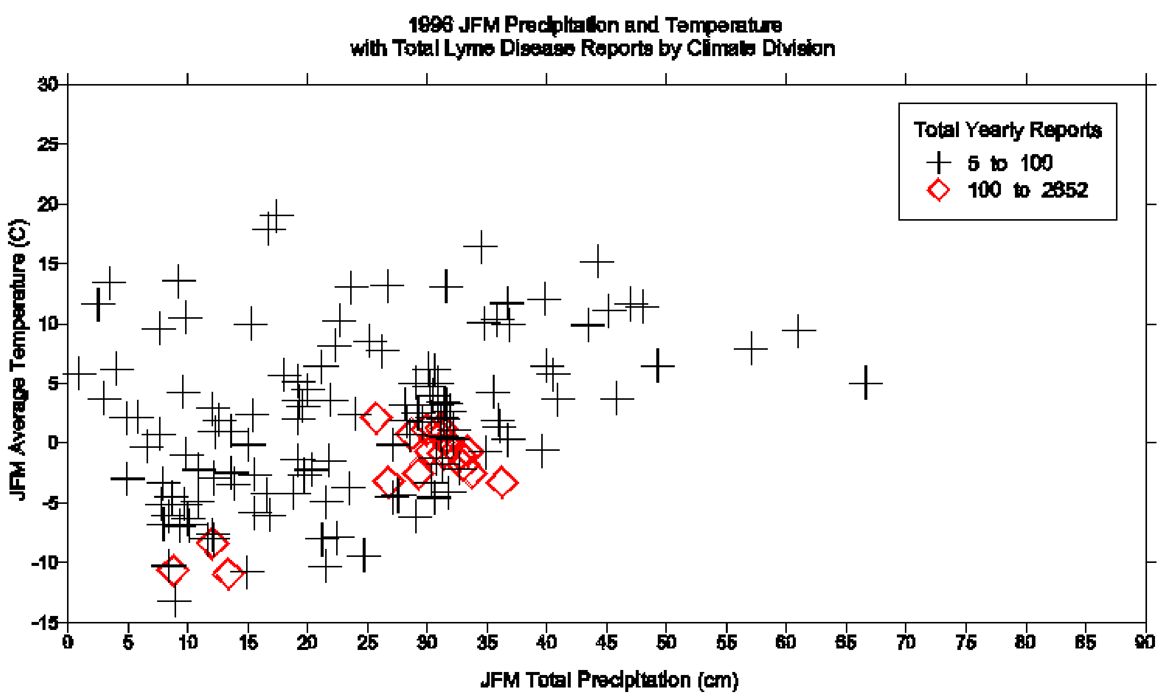

Figure B.7: Graph of 1996 JFM precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

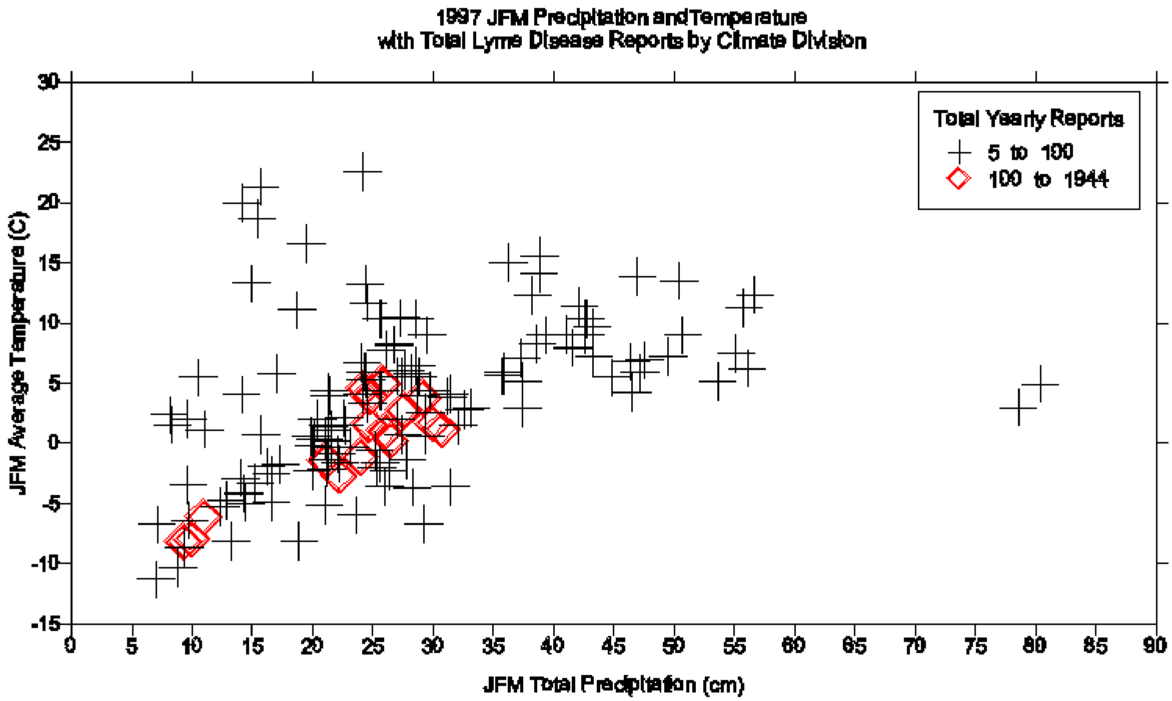

Figure B.8: Graph of 1997 JFM precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

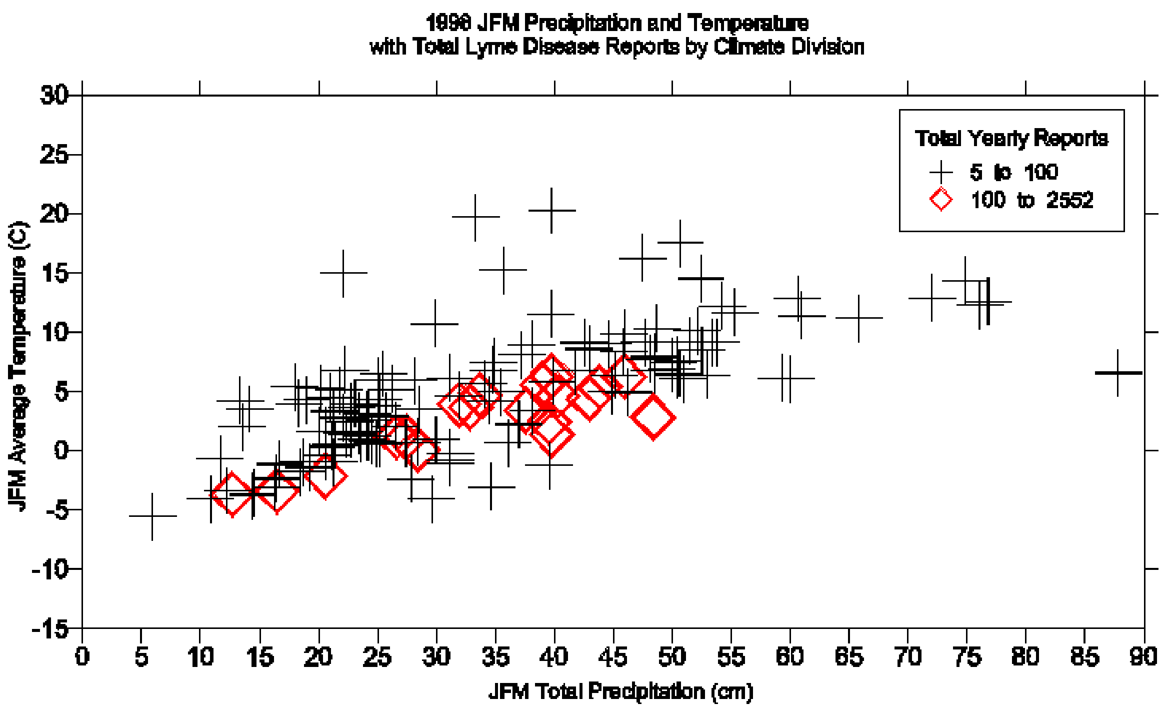

Figure B.9: Graph of 1998 JFM precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

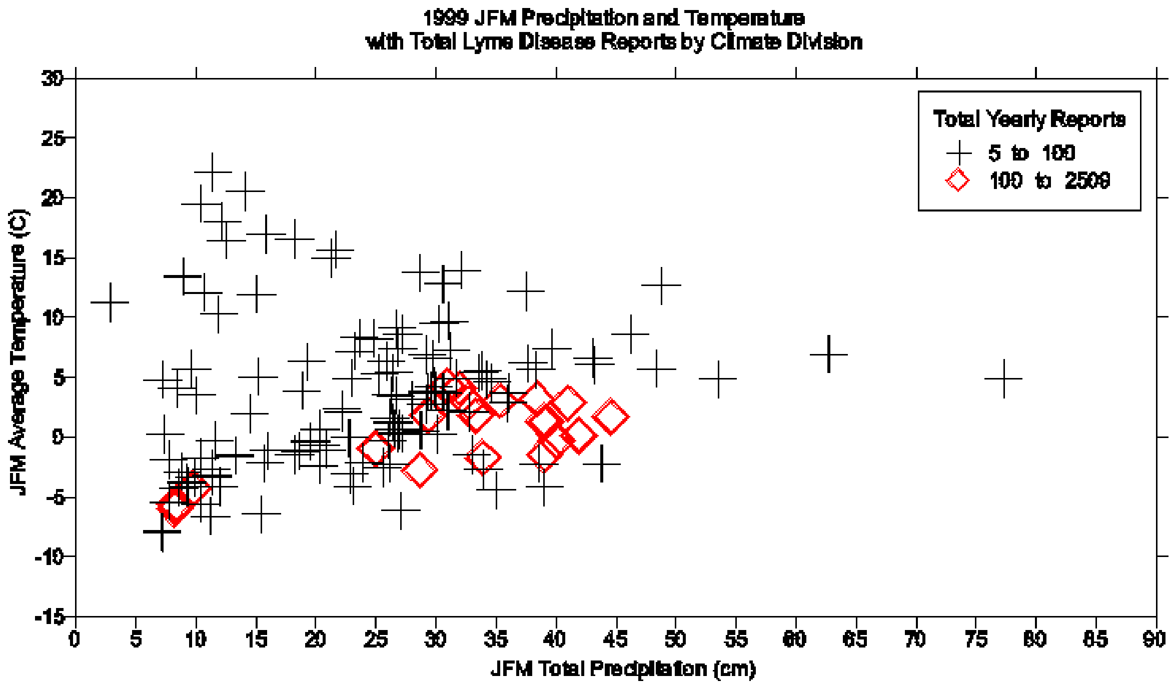

Figure B.10: Graph of 1999 JFM precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

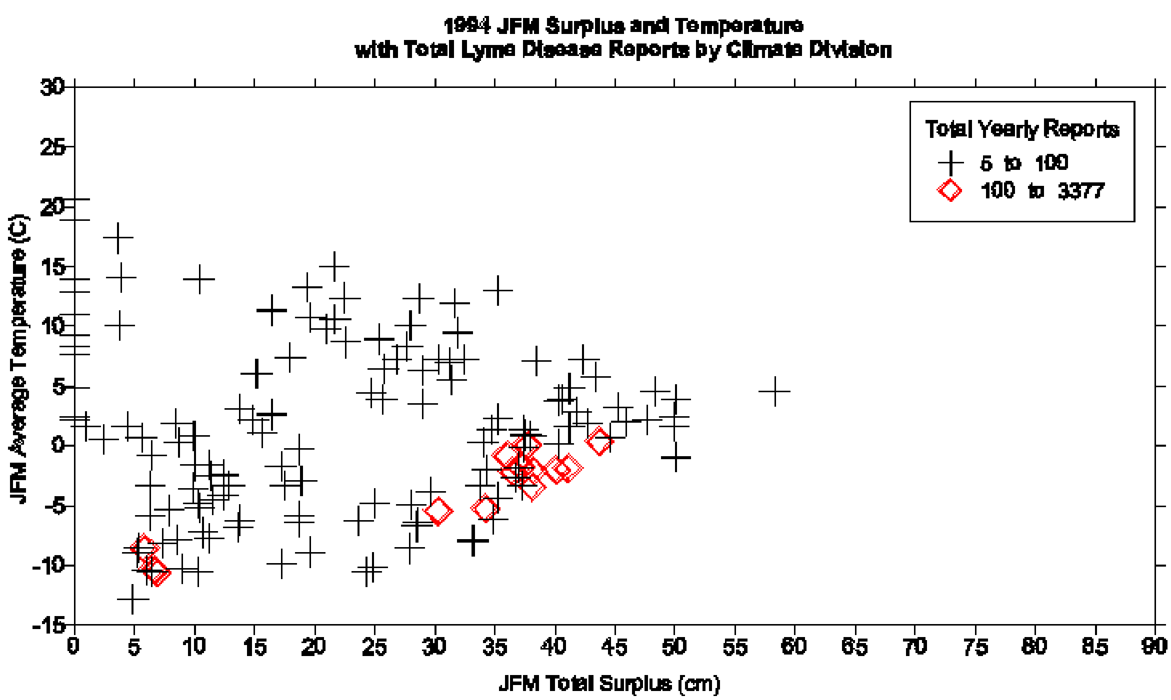

Figure B.11: Graph of 1994 JFM surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

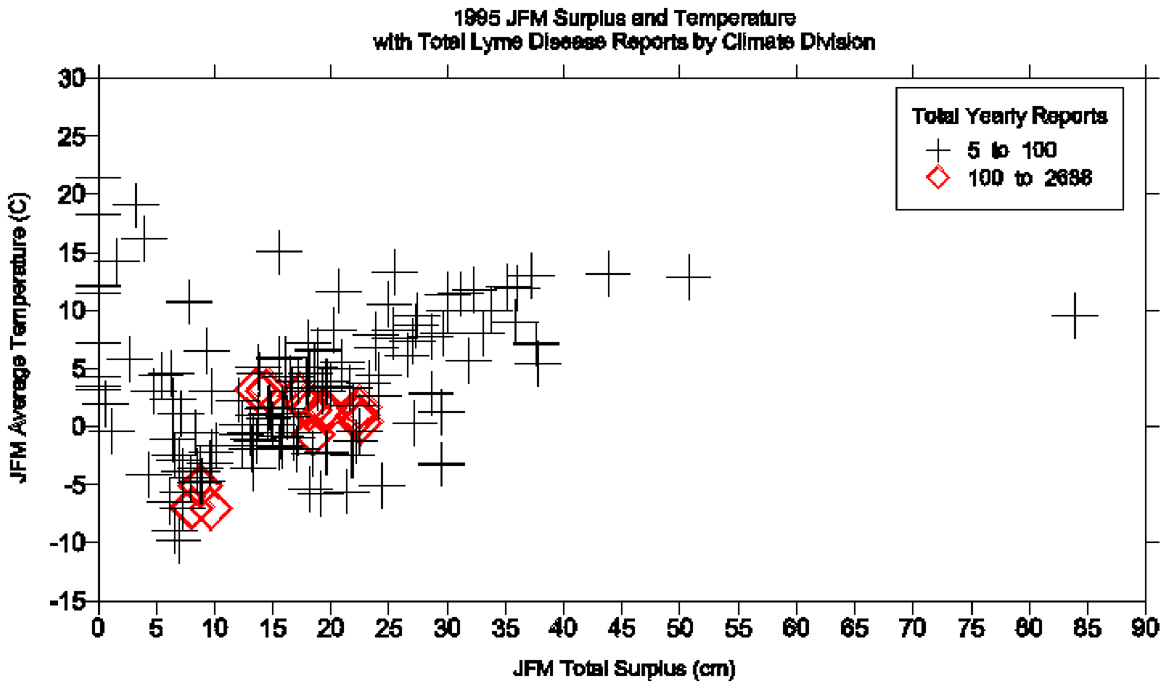

Figure B.12: Graph of 1995 JFM surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

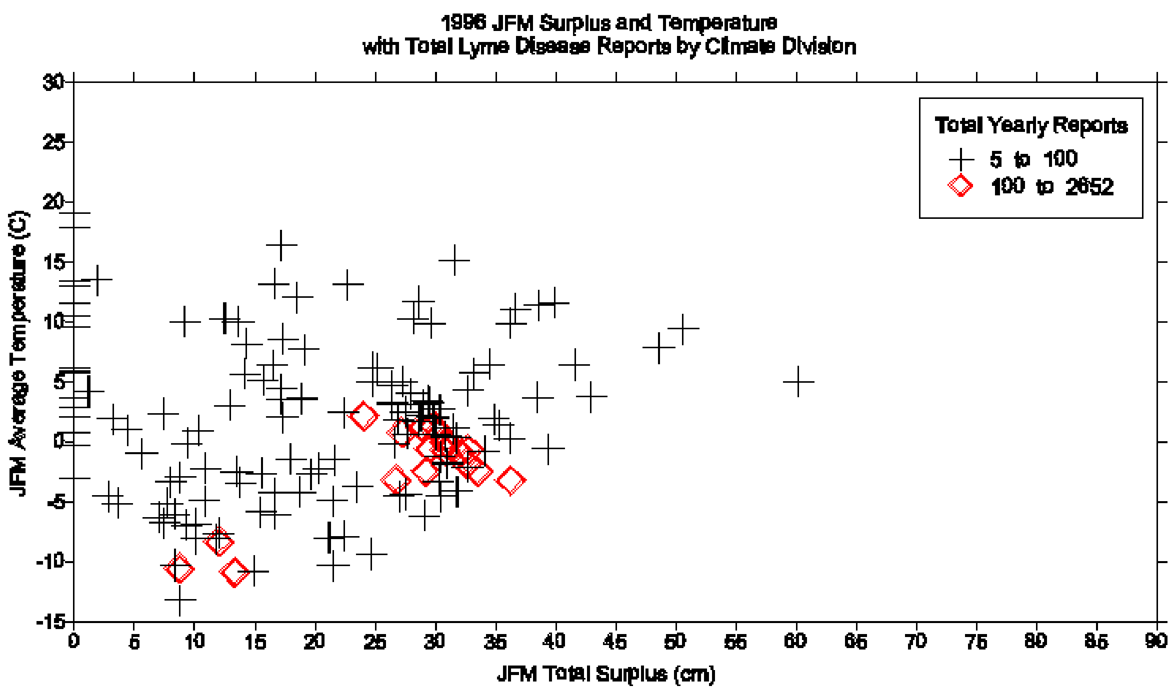

Figure B.13: Graph of 1996 JFM surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

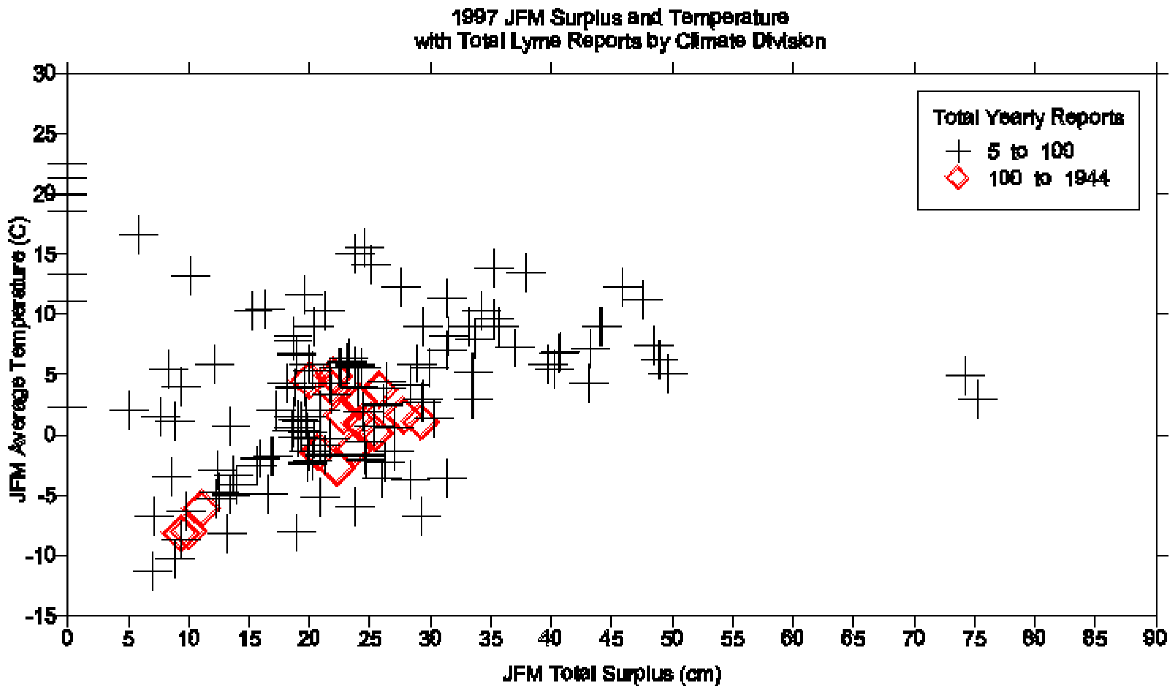

Figure B.14: Graph of 1997 JFM surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

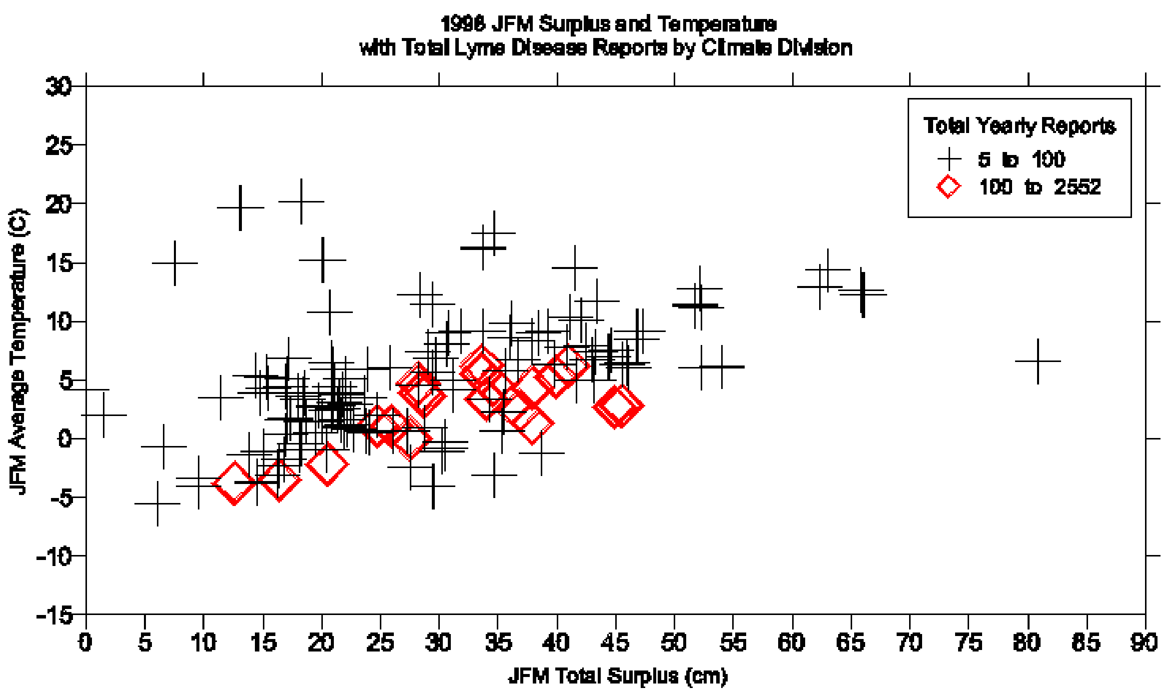

Figure B.15: Graph of 1998 JFM surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

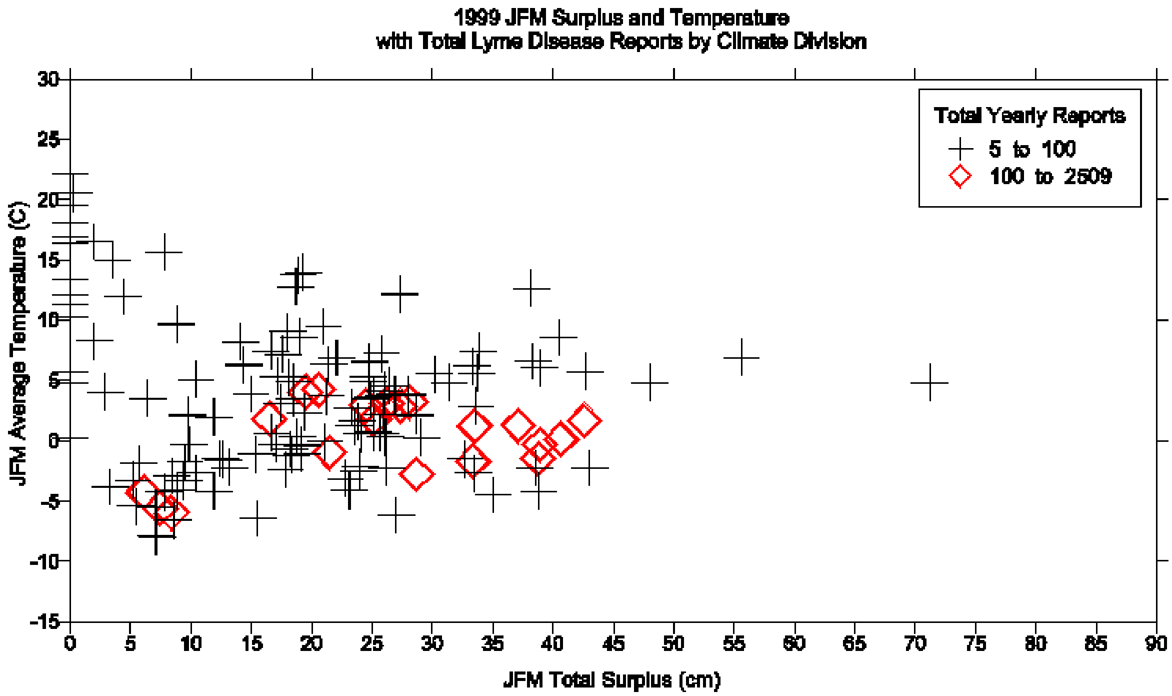

Figure B.16: Graph of 1999 JFM surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

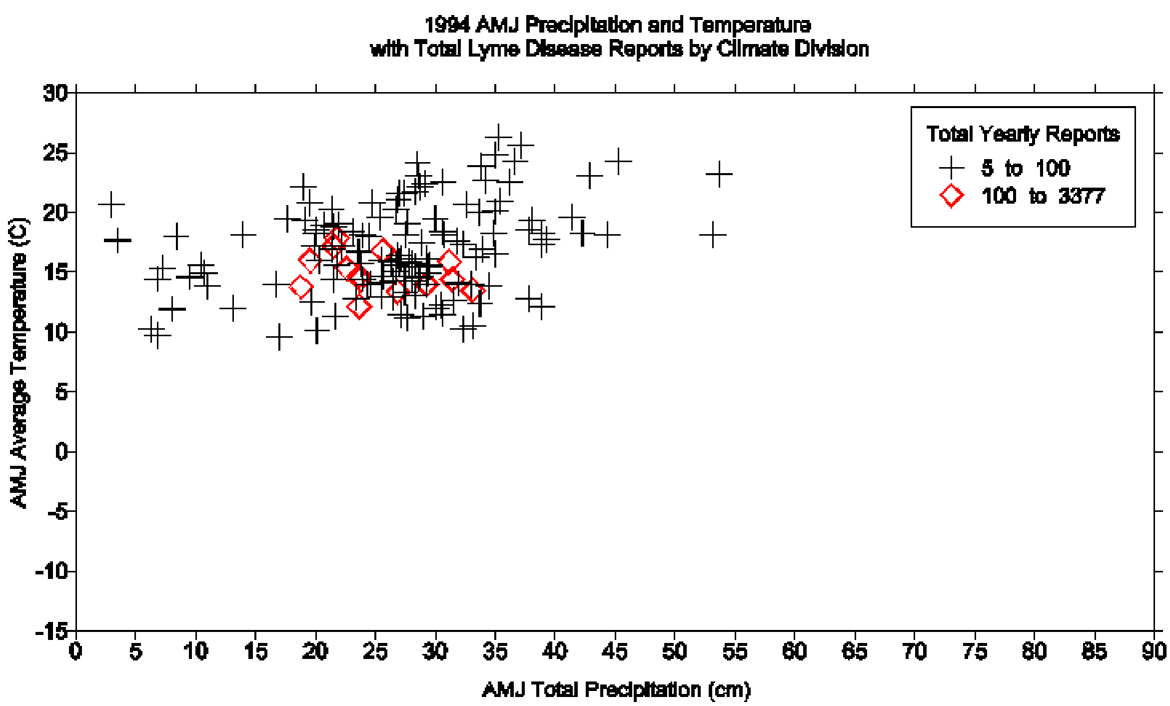

Figure B.17: Graph of 1994 AMJ precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

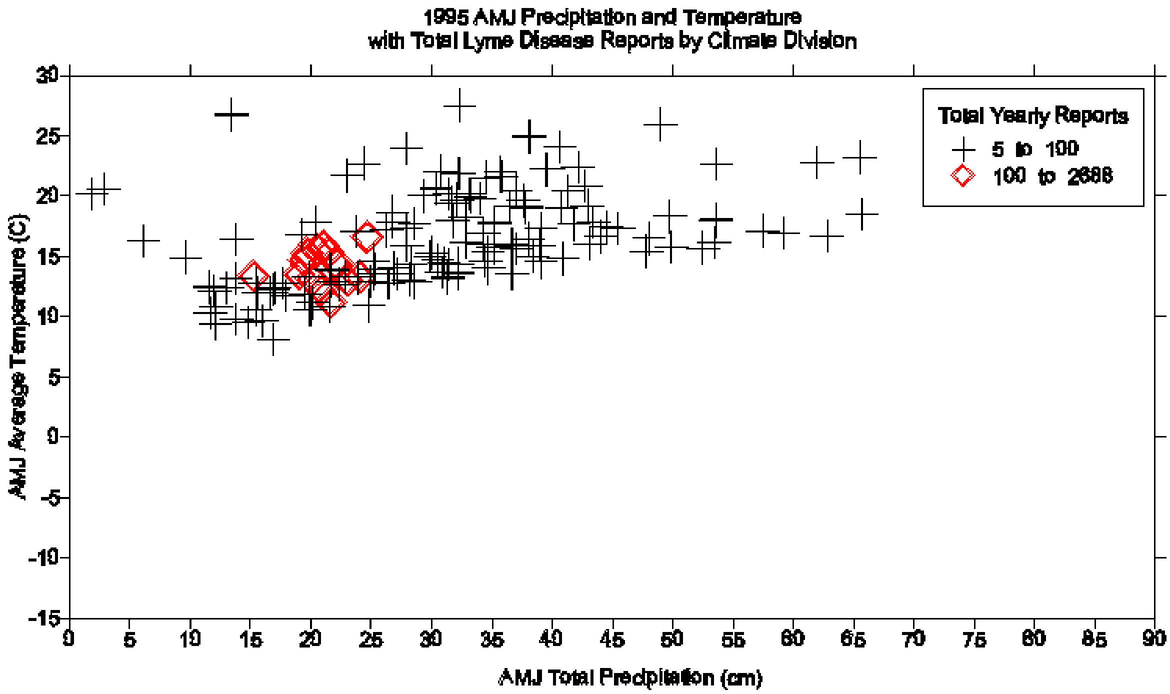

Figure B.18: Graph of 1995 AMJ precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

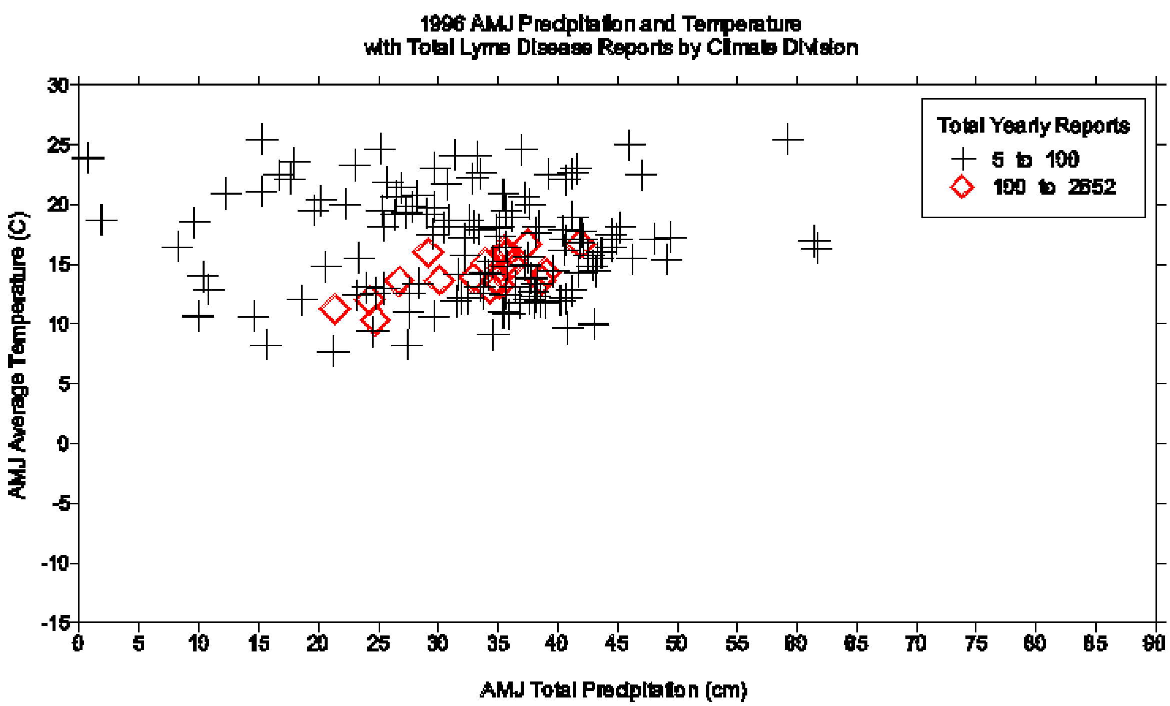

Figure B.19: Graph of 1996 AMJ precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

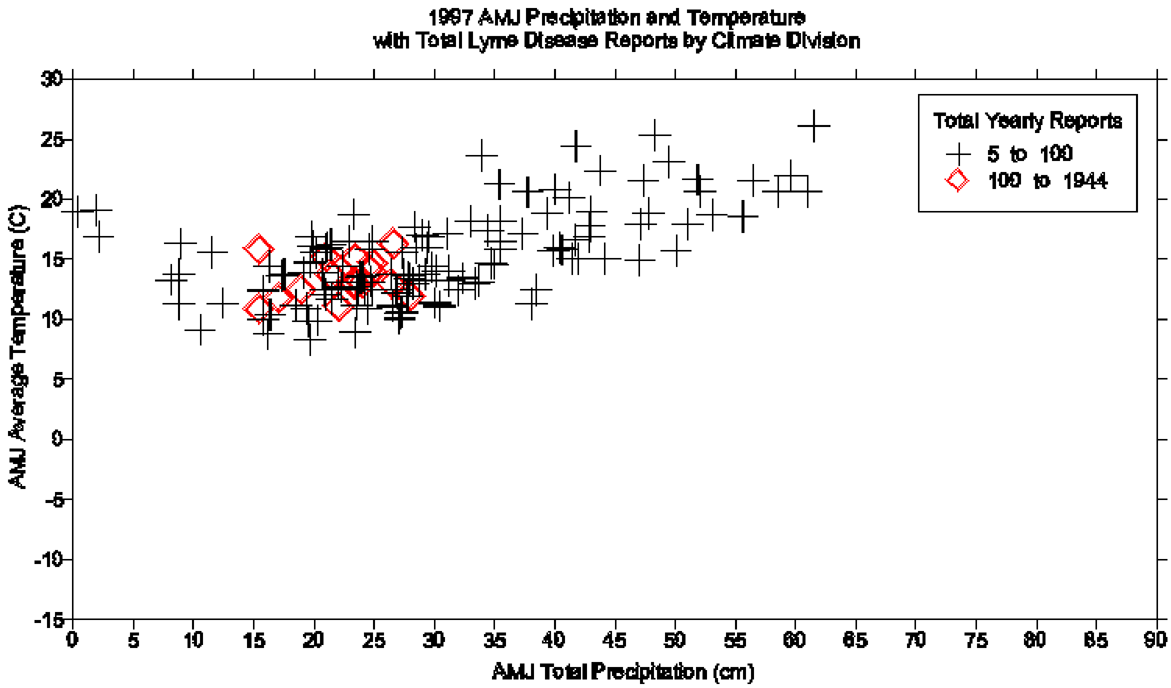

Figure B.20: Graph of 1997 AMJ precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

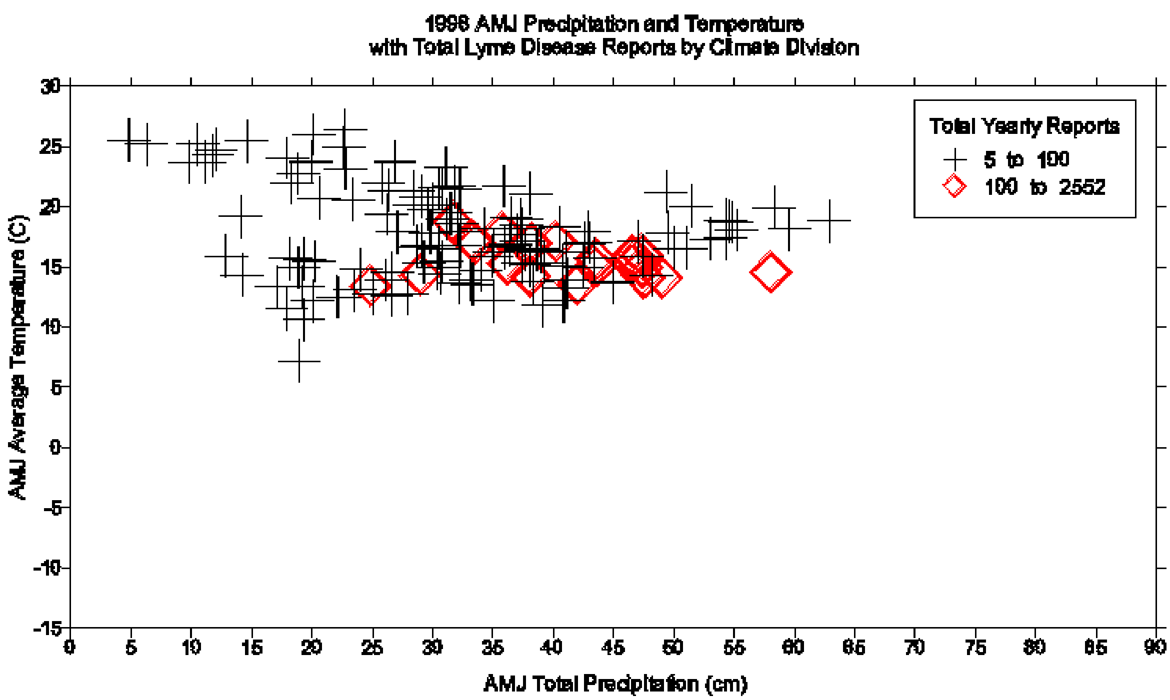

Figure B.21: Graph of 1998 AMJ precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

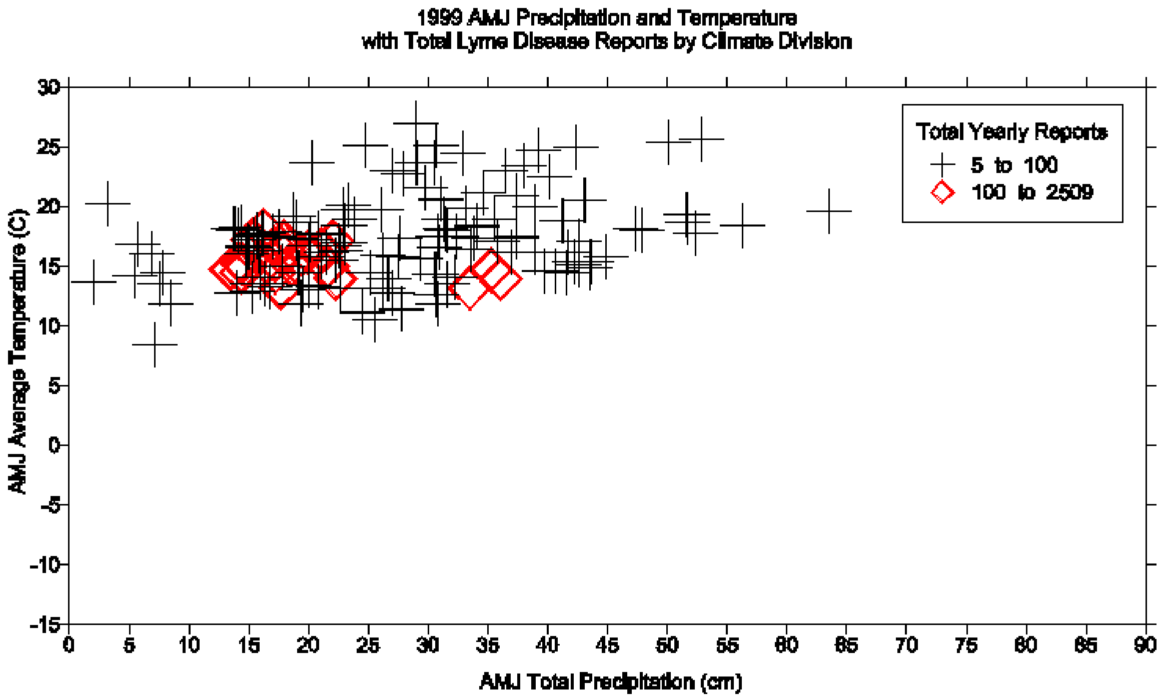

Figure B.22: Graph of 1999 AMJ precipitation and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

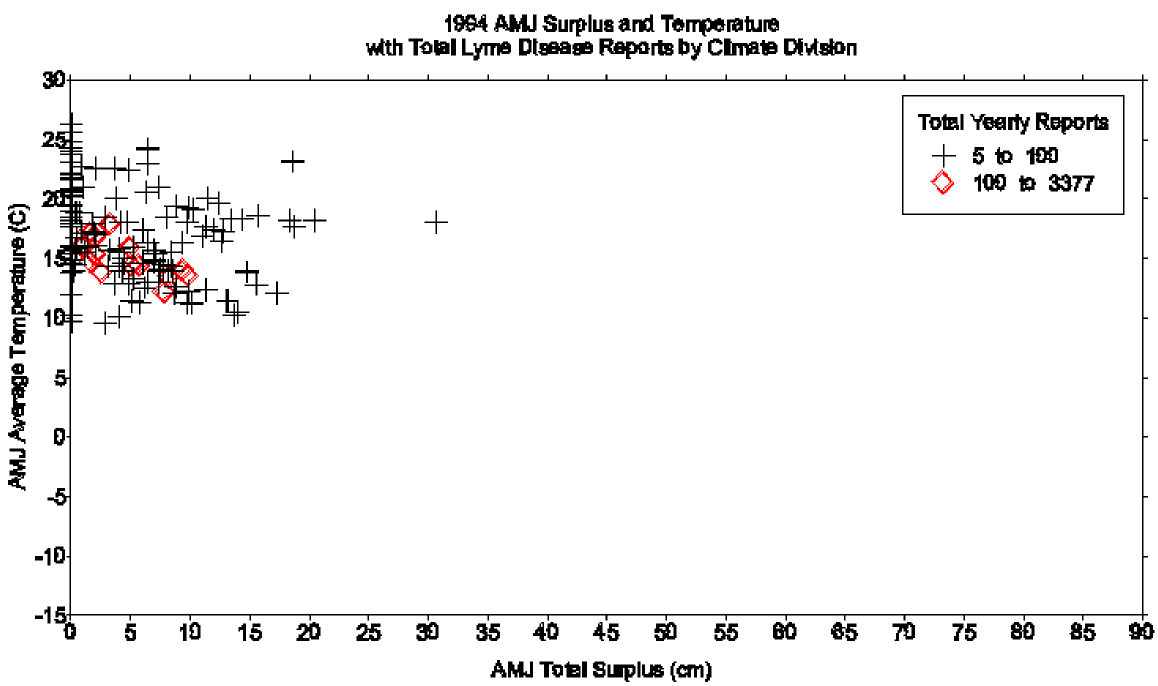

Figure B.23: Graph of 1994 AMJ soil moisture surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

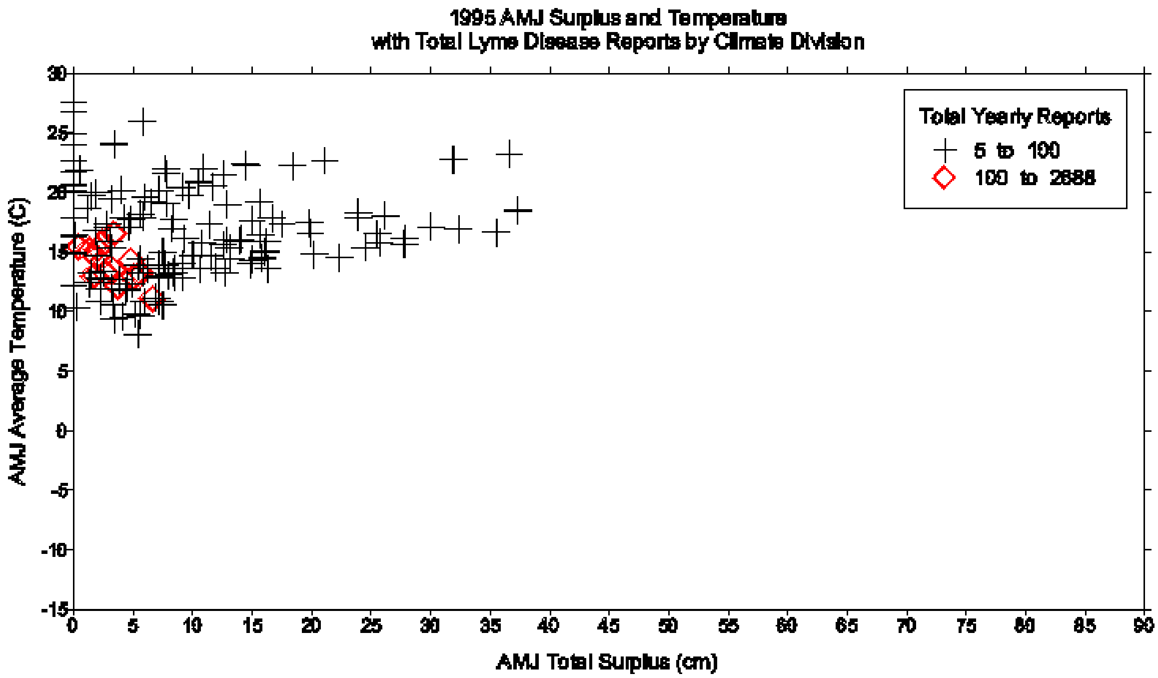

Figure B.24: Graph of 1995 AMJ soil moisture surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

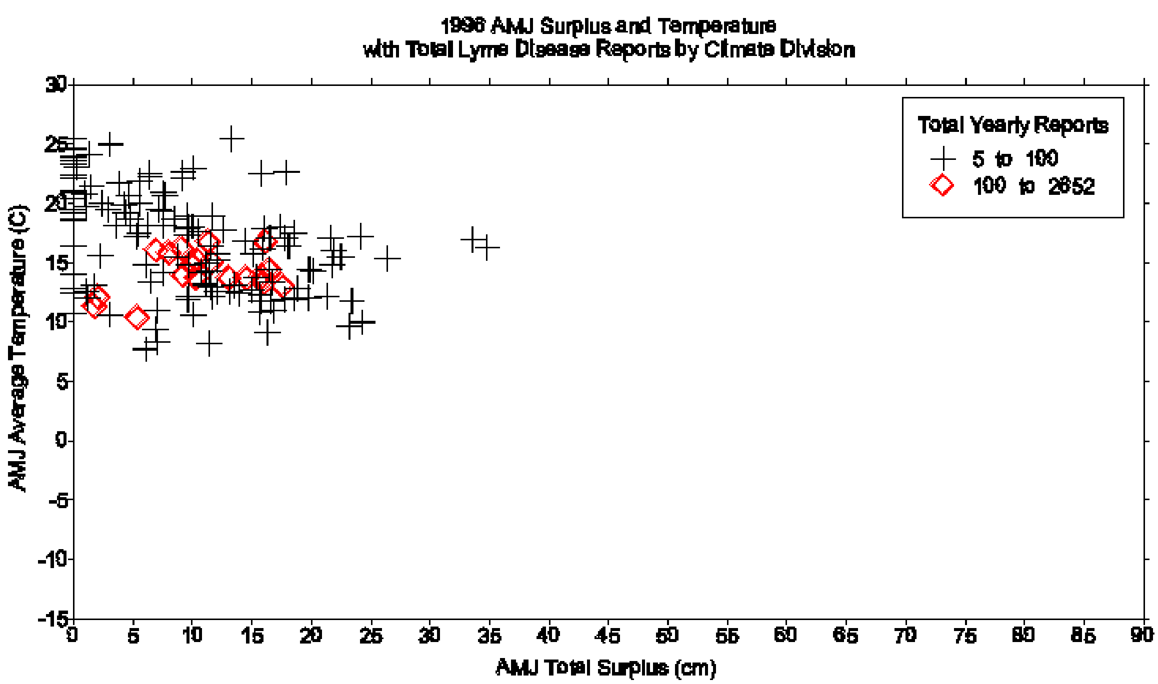

Figure B.25: Graph of 1996 AMJ soil moisture surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

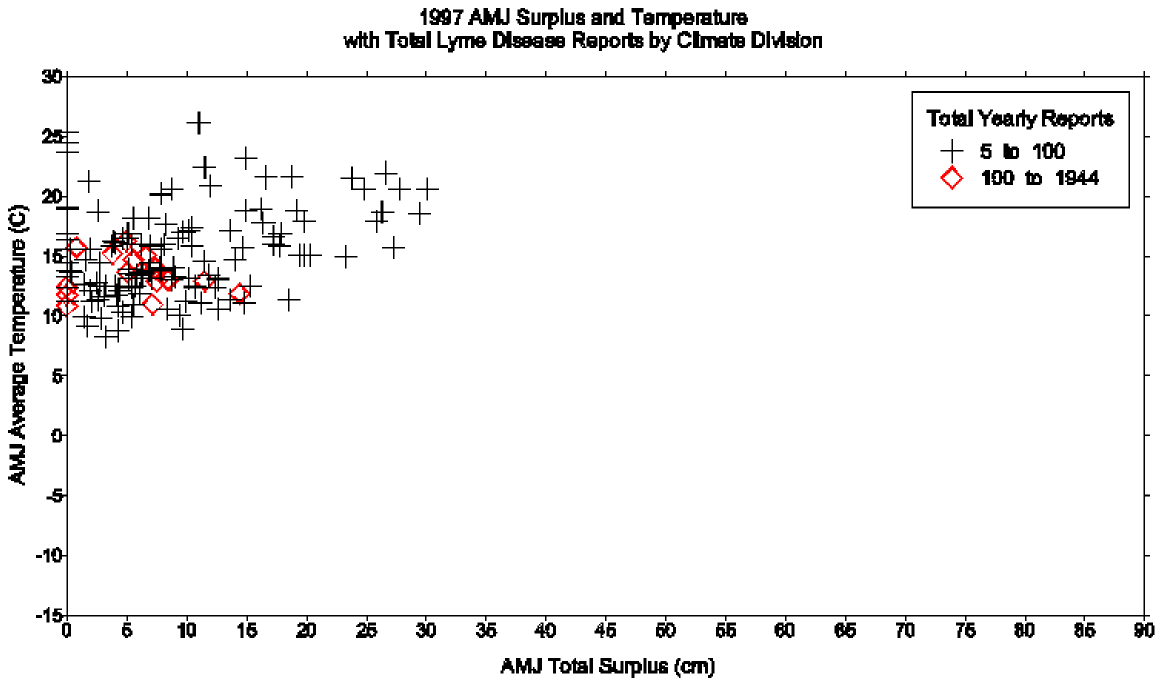

Figure B.26: Graph of 1997 AMJ soil moisture surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

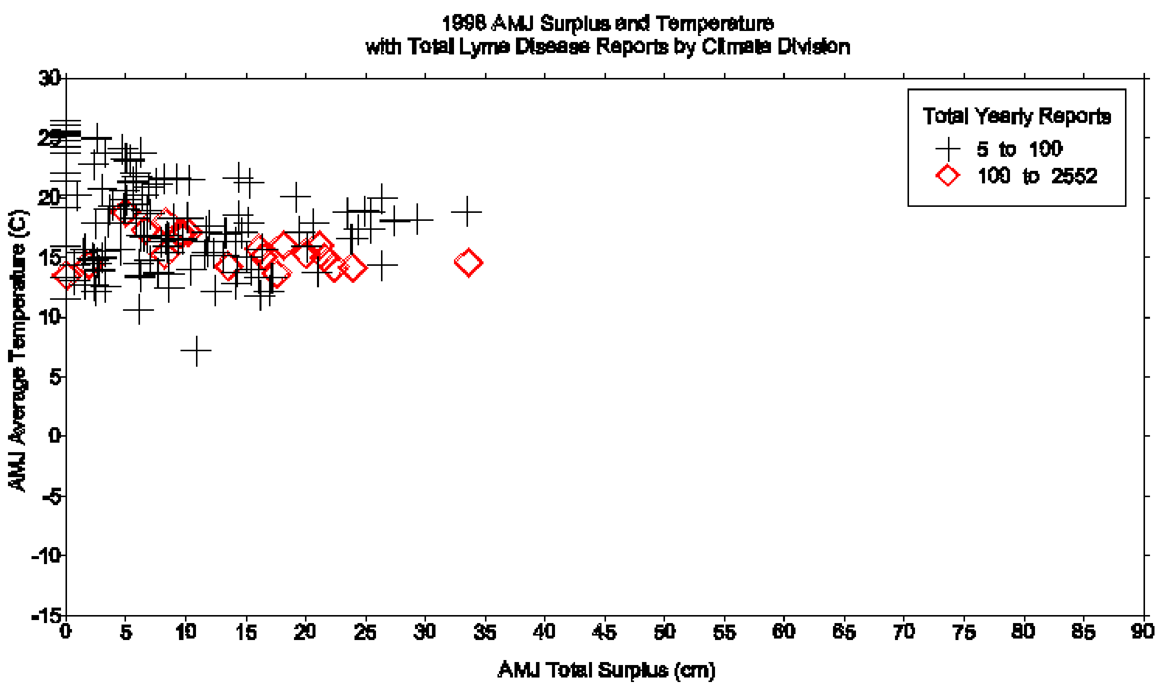

Figure B.27: Graph of 1998 AMJ soil moisture surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.

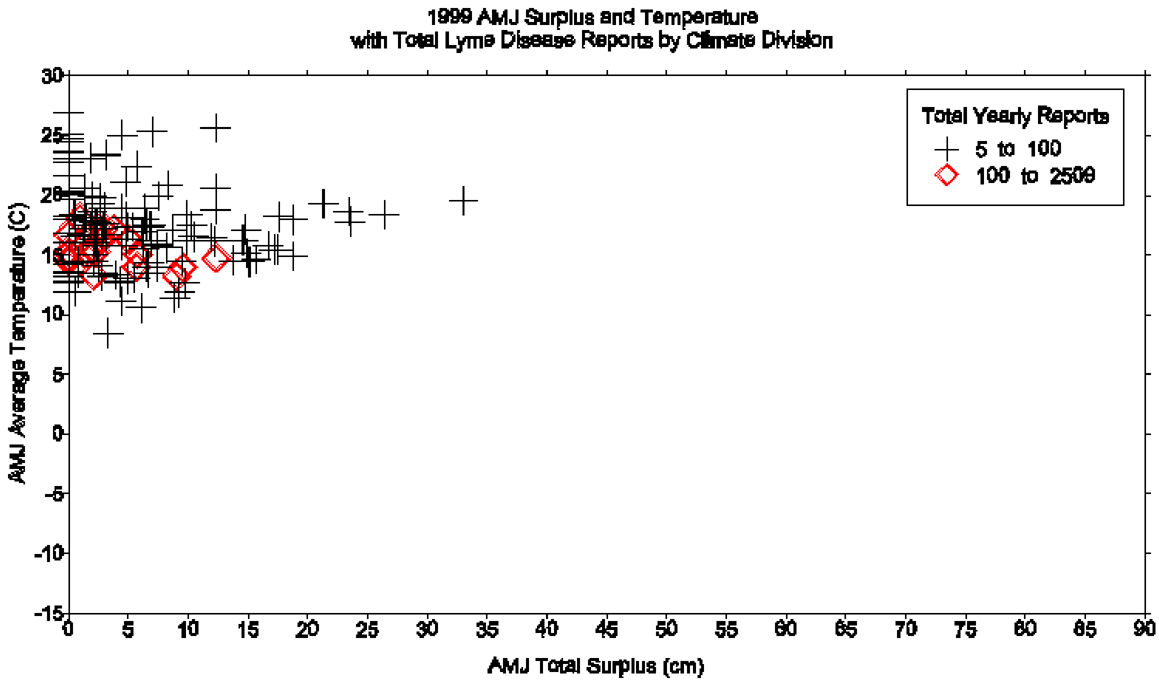

Figure B.28: Graph of 1999 AMJ soil moisture surplus and temperature values with corresponding yearly reports by climate division based on data from 1994 to 1999.