Vol. 27: 177–187, 2004 | CLIMATE RESEARCH Clim Res | Published December 8

Climatic analysis of Lyme disease in the United States

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ABSTRACT: This study demonstrates that climatic variables in April, May, and June have strong relationships with Lyme disease rates in the USA during the peak summer season. The disease system appears to be constrained more by moisture than temperature. A predictive 'climatic envelope' model is developed based on mean air temperatures, total precipitation, and total soil moisture surplus values for the months of April, May, and June. The middle 90% of cases with greater than 10 reports per 100 000 people for the 1994 to 1999 reporting period occurred in counties with an average temperature in April, May, and June between 10.8 and 19.4°C, total soil moisture surplus values of 1.3 to 13.2 cm, and total precipitation values of 19.7 to 37.8 cm. This simple model is used to produce a risk map for Lyme disease that identifies the peak incidence regions in the Northeast and upper Midwest as well as regions that are in the suitable climate range for the disease to be endemic but in which the disease is currently rare or non-existent.

KEY WORDS: Climate · Geography · Lyme disease · Seasonality · Climate envelope model

1. INTRODUCTION

Lyme disease, a common arthropod-borne disease in the United States, was first discovered in 1977 in Lyme, Connecticut (Orloski et al. 2000). This disease is caused by a spiral-shaped bacterium, *Borrelia burgdorferi*, which belongs to the family Spirochetes (Burgdorfer 1982, Dennis 1998). Lyme disease is spread by ticks of the genus *Ixodes* that are infected with the bacterium. In the Northeast, north-central and southern United States, the deer or black-legged tick *Ixodes scapularis* (formerly known as *Ixodes dammini*; Oliver et al. 1993) is responsible for the transmission of the disease, while on the Pacific coast it is transmitted by the western black-legged tick *Ixodes pacificus* (Shapiro & Gerber 2000, Eisen et al. 2002).

Lyme disease is formally defined as 'a systemic, tick-borne disease with protean manifestations, including dermatologic, rheumatologic, neurologic, and cardiac abnormalities. The best clinical marker for the disease is the initial skin lesion (i.e. erythema migrans [EM]) that occurs in 60 to 80% of patients' (Center for Disease Control and Prevention [CDC] 1997). According to the CDC, EM is 'a skin lesion that typically begins as a red macule or papule and expands over a period of days to weeks to form a large round lesion, often with partial central clearing. For most patients, the expanding EM lesion is accompanied by other acute symptoms, particularly fatigue, fever, headache, mildly stiff neck, arthralgia, or myalgia' (CDC 1997).

The majority of Lyme disease cases occur in the Northeast, mid-Atlantic states (Massachusetts to Maryland) and the upper Midwest (Minnesota and Wisconsin), although a smaller endemic focus is located in the far western U.S. (i.e. California and Oregon). The spatial distribution of the disease is shown in Fig. 1 and includes the years 1994 to 1999. While this map is similar to previous maps produced by the CDC, the time periods analyzed and mapped differ. In the Northeast and north-central U.S., May through August have the highest reports, with June and July generally being accepted as the peak months (Gubler et al. 2001, Subak 2003).

Lyme disease has been termed a 'resurging' disease and is distributed globally (Gratz 1999). It is suspected that the resurgence is caused not only by the establishment of the vector but also climate, immunity status,

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

density of human populations, and presence of a suitable reservoir host (Gratz 1999). A region's climatic characteristics show links to arthropod-borne disease vectors (including their distribution, seasonal activity, and behavior), the vector's hosts, and the vector's transmission cycle (Daniel & Dusbabek 1994, Gubler et al. 2001). Climatic factors such as temperature, rainfall, and humidity are important in the presence or absence of the arthropod-borne diseases since 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. Moreover, temperature and moisture characteristics may affect the reproductive processes of both pathogen and vector (Loper 1999).

Atmospheric humidity plays an important role in the tick's water balance; it may therefore be of importance to the survival of ticks (Knulle & Rudolph 1982). This can be seen during the tick's non-feeding periods throughout a given year due to dehydration to the atmosphere. However, when high humidity is coupled with moderate temperatures, the tick is able to gain the needed water from the atmosphere within its sheltered microclimate of forest litter. The water balance of the tick is most critical when the tick emerges from the forest ground and ventures out into bare soil or up onto vegetation to seek its host. In general, most tick species have a threshold atmospheric humidity at which the tick will continually lose water, approximately 75 to 94 % (Knulle & Rudolph 1982).

According to Keirans et al. (1996), Lyme disease 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). Accordingly, the microclimate 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 ticks mostly limit themselves to deciduous woodlands where large animals (e.g. deer) are abundant, although they can be found in coniferous forest as long as the leaf litter is sufficient and the climate is moist (Dennis et al. 1998). The density and distribution of leaf litter in the tick's habitat is an important factor in its survival since 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 March and June by 72.7 to 100 % (Schulze et al. 1995).

Studies of the seasonal and spatial distributions of Lyme disease focus on either the presence and abundance of the vector itself (*Ixodes scapularis or I. pacificus*) or on the reported human cases of the disease. Recent work by Estrada-Peña (2002) and Brownstein et al. (2003) are excellent examples of attempts to model the distribution and abundance of *I. scapularis* based on climate variables. Estrada-Peña (2002) used the distribution of the tick dating back to 1998 along with temperature and Normalized Derived Vegetation Index (NDVI) derived from satellite data to model the change in tick habitat from 1982 until 2000. It was concluded that an increase in winter temperatures and increased rainfall make a region suitable for habitation. Brownstein et al. (2003) created a model to improve the distribution map of the tick as well as determine potential areas of disease risk based on temperature and humidity variables. Additionally, Subak (2003) attempted to find a climate versus incidence relationship by examining state level Lyme disease incidence data in relation to summer moisture index and winter temperatures. June moisture index (using Palmer Hydrological Drought Index) levels 2 yr previous were most strongly linked to Lyme disease incidence.

Several studies have been conducted to examine the effects of meteorological variables on the activity, density, distribution and survival of the deer tick *Ixodes scapularis*, including Duffy & Campbell (1994), Stafford III (1994), Lindsay et al. (1995), VanDyk et al. (1996), Vail & Smith (1998), Jones & Kitron (2000), Schulze et al. (2001), Estrada-Peña (2002), and Brownstein et al. (2003). Similar to the aforementioned studies, Eisen et al. (2002) examined the seasonal activity pattern of *Ixodes pacificus* nymphs. Additionally, research has examined the effect that varying temperature has on the actual bacterium, *Borrelia burgdorferi* (Shih et al. 1995). Other studies examine reservoirs for the bacterium in order to determine the range of animals capable of carrying this tick-borne disease and the ability that these animals have in maintaining the disease bacterium (Gray et al. 1992, Mather & Ginsberg 1994, Keirans et al. 1996, Gray 1998).

Past research has determined that there are indeed relationships between climatic factors and vector-borne diseases. The seasonality of the disease has often been reported, which suggests that climatic variables probably enter into the epidemiology of Lyme disease. The relationship between climate and the vector is of obvious importance in determining the impact of climatic variables on the spatial distribution of Lyme disease across the country. However, the presence of the black-legged tick by itself does not indicate the actual occurrence of Lyme disease. Moreover, models of the potential for tick presence (i.e. Estrada-Peña 2002, Brownstein et al. 2003) do not exactly match the occurrence of the disease. This research will initiate the investigation to search for any relationship that climatic variables have with Lyme disease rates on the county geographic level.

Specifically, this study examines the relationship between the climatic parameters of monthly time periods leading up to the peak reporting months (June, July, and August), and the geography of the disease. Variables including mean monthly temperature, total monthly precipitation, and total monthly soil moisture deficit and surplus values are statistically related to Lyme disease rates. Thus, the months are identified where climate is most influential on the disease, and it is determined whether there is a most suitable climatic habitat for Lyme disease to thrive. Additionally, the geographic areas that are within the suitable climate to support the disease are found using a 'climate envelope' model. The model is created based on the results from the 2 initial analyses (1 variable and 2 variable). The model is intentionally simple, so that it may be understood across disciplines.

2. DATA AND METHODOLOGY

The Lyme disease report data were collected from the CDC and include raw county Lyme disease reports by year for the time period 1994 through 1999. The CDC compiles Lyme disease data through the Division of Public Health Surveillance and Informatics under the National Notifiable Disease Surveillance System (NNDSS). The list of nationally notifiable diseases is updated periodically and based on a policy agreed between the CDC and the Council of State and Territorial Epidemiologists (CSTE). Notifiable diseases must be reported to the NNDSS (CDC 1997). In October of 1990, the CDC published case definitions of each disease, therefore making the reporting by state uniform due to the uniformity of criteria used to identify the diseases. A notifiable disease is defined by the CDC as 'one for which regular, frequent, timely information on individual cases is considered necessary to prevent and control that disease.' For the time period used for this study, Lyme disease is listed as a nationally notifiable disease. NNDSS data are considered to represent the minimum number of case counts and, in general, the disease cases are reported to the county of residence regardless of where the infection occurred.

The temperature, precipitation, and soil moisture values are monthly and 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; www.ncdc.noaa.gov). Soil moisture data, also given by climate division, were generated using a program based on the Thornthwaite-Mather climatic water budget technique (Thornthwaite & Mather 1955). The program utilizes monthly temperature and precipitation data by climate division as well as soil field capacity values taken from Main (1979) in order to generate the soil moisture values. For a detailed description of this technique, see Leathers et al. (2000).

Climate divisions are based on the climate of a given state and the divisions are based on like climatic regimes of regions in that state. Each of the 48 contiguous states is divided into between 4 and 10 climate divisions. The climate divisions were matched with the county Lyme disease data. Fortunately, the climate divisions for each state coincide for the most part 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 in which greater than half of its area is located.

It must be noted that the optimal Lyme disease data set (monthly cases by county) was unavailable to the authors. Despite this problem, the data available to the authors underwent thorough analyses in order to seek a link between climate and Lyme disease. The conclusions reached are strictly based on county level Lyme disease data and climate division climate variables; therefore, results may differ when analyzed at different geographic levels.

Nicholson & Mather (1996) conclude that the incidence of Lyme disease corresponds highly with the local density of ticks infected with *Borrelia burgdorferi*; therefore, this study is based on that assumption. A compilation of *B. burgdorferi*-infected tick density data on a large scale (i.e. continental U.S.) was unavailable for the time period of the study as its initiation was in 1998. Moreover, tick density data merely show the distribution of the tick, not the presence of *B. burgdorferi*. Therefore, this study uses Lyme disease reports as a surrogate for actual data on tick density, human-tick contacts, and the presence of *B. burgdorferi*. The period between the time that the tick becomes attached to a person and the onset of the illness is several weeks to months (Barbour 1996). Despite the extreme variability of the seasonality of Lyme disease, the overall peak season of incidence (June, July, and August) will be used to investigate any apparent climatic controls entering into the disease since this is the time when the disease peaks in the 2 main endemic areas of the Northeast and upper Midwest. Therefore, these main endemic areas are focused on for this analysis.

The influence of climatic variables on the tick is an important relationship due to the strong correlation found between Lyme disease and local density of *Borrelia burgdorferi*-infected nymphal deer ticks in the northeastern and mid-Atlantic U.S. (Nicholson & Mather 1996). It must be noted that the particular macroclimate that coincides with counties with high case rates is only an indication of where the disease might be found; 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 components necessary for the transmission of the disease from host to vector to human must be sufficiently abundant in regions within the optimal climate. If one or more of the components is absent, the cycle of transmission will not be completed.

2.1. Single variable analysis

To determine the months most influential on the disease, average annual cases adjusted by population (1994 to 1999) are plotted against average single climate variables by month and graphed for consecutive monthly time periods throughout the calendar year. These climate variables include average precipitation totals, average temperature, average soil moisture surplus totals, and average soil moisture deficit totals. There are 12 time periods each including 3 months of data beginning with January, February, March (JFM) and continuing through the months of the year one month at a time (i.e. sliding window). Although the life cycle of *Ixodes scapularis* ticks spans 2 yr, lagged effects of climate variables on disease occurrence were not examined since the data was analyzed as an average for the study period. From these plots the potential influence that climate has on the disease can begin to be understood. The spread or range of climatic values (i.e. mm of precipitation) plotted against the disease demonstrates this concept. For each 3 mo period, the time period that is most closely related to the tick and transmission of the bacterium should be the one with the narrowest range of climatic values. Thus, less spread indicates that the time period is more highly related with high Lyme disease reports.

2.2. 'Climate envelope' analysis

Unfortunately correlation/regression methods are not well suited for this analysis because of the continental scale causing relationships between Lyme disease cases and climatic variables to be extremely curvilinear. This was determined during the initial phases of investigation into the relationship between adjusted Lyme disease cases and the climate variables (namely, precipitation and temperature). Bivariate plots showed that the relationship was not linear, but resulted in a bell-shaped curve. It was found that peak rates of cases occur within a narrow range of the climate variable, indicating that there are climate conditions that are too low and too high to support the disease vector.

A concept introduced by Hutchinson (1957) and founded on the 'fitness' or 'tolerance' between an organismic unit and some environmental gradient (variable), the 'fundamental niche', allows one to describe the activity range of a species along environmental dimensions (Pianka 1974). Specifically, the 'fundamental niche' is a 'hypothetical idealized niche in which the organism encounters no "enemies" such as competitors and predators and in which its physical environment is optimal' (Pianka 1974). Although this study covers the entire Lyme disease system (including the tick, host, and human), the Gaussian distribution found supports the 'niche concept'. Therefore, a second analysis implementing the 'fundamental niche' or 'climate envelope' was utilized. This method is similar to those used successfully to predict vegetation patterns at continental to global scales (Box 1981, Crumpacker et al. 2002).

This method attempts to find the upper and lower limits of at least 2 climatic variables for counties with high report rates. High report rates are those with ≥100 average annual cases per 100 000 people, which, by happenstance, is indicative of the top 5% of case rates used in this analysis. Unlike previous analysis, the plots only show counties with >5 average (1994 to 1999) annual Lyme disease cases per 100 000 people. Only counties with ≥5 average annual cases are used, in order to eliminate counties with zero reports and counties with <5 cases. Counties with <5 cases were marked with an asterisk in the initial Lyme disease database issued through the CDC and were assigned a value of 2.5 by the authors (as instructed by the CDC); therefore, they are removed from this analysis due to uncertainties. Average annual Lyme disease cases by county are placed into 2 numerical classes, represented by a symbol, and plotted against 2 climate variables instead of the previous 1 climatic variable (see Figs. 8 to 11).

2.3. 'Climate envelope' model

The 'climate envelope' model shows counties that are within the upper and lower limits of the climate variables for the 'best-fit' 3 mo time period determined by the single variable and 'climate envelope' method analyses. These upper and lower limits are determined by the range of climate values of the counties in the middle 90th percentile of all counties with ≥10 average annual cases per 100 000 people. The middle 90th percentile was found by calculating the median of the climate values of counties with >10 average annual cases per 100 000 people (155 counties). Subsequently, the range included the climate values from 45% to the right and left of the median. Only counties with >10 average annual cases are used so that rare occurrences of the disease (i.e. misdiagnosis and/or misreporting of county where the disease was contracted) are omitted. The climate model is based upon a 'word' equation of the following form:

Predicted 'Favorable Climate' = (Range of Avg. Total Precipitation Values) + (Range of Avg. Total Soil Moisture Surplus Values) + (Range of Avg. Temperature Values)

Counties that fall within the climatic boundaries depicted by this equation were mapped using ArcView v3.2. This indicates counties that meet the climatic requirements to support at least 10 average annual cases per 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. The boundaries do show counties in which the disease could potentially spread most easily.

3. RESULTS: SINGLE VARIABLE ANALYSIS

Interestingly, in examining the series of plots of each climatic variable, a secondary peak located in lower values of climatic variables for the precipitation, temperature, and moisture surplus plots from the time period of September, October, November (SON) through March, April, May (MAM) is evident (not shown). This secondary peak merges with the primary peak in the April, May, June (AMJ) to August, September, October (ASO) plots and corresponds to the smaller endemic area in the upper Midwest (Minnesota and Wisconsin). The upper Midwest region has a colder and drier winter compared to the Northeast winter.

A comparison of all the single variable relationships shows that the 3 mo periods of April, May, June (AMJ) and June, July, August (JJA) have a smaller degree of spread (more narrow ranges) of their plots for precipitation, temperature, and moisture surplus compared to the remaining time periods (Figs. 2 to 7). More specifically, in comparing the spread of the AMJ and JJA plots, Fig. 2 shows that the AMJ time period has a smaller spread for precipitation values, whereas it is evident in Figs. 5 & 7 that the JJA time period has a smaller spread for both the temperature and moisture surplus values. Furthermore, examination of the AMJ and JJA plots of all 3 climatic variables shows that the spread is more compact for the AMJ precipitation values than the spread of either the temperature or moisture surplus values. This leads to the tentative conclusion that precipitation may have a stronger relationship to the rates of Lyme disease than either temperature or soil moisture surplus in JJA.

For each of these 3 mo periods, a majority of the counties in the U.S. have soil moisture deficits of less than about 6 cm. They are 'moist' counties (i.e. little to no soil moisture deficits) in late winter and early spring. Some of these counties have very low numbers of average annual Lyme disease cases but others are in the highly endemic area of Lyme disease. By contrast, of the coun-

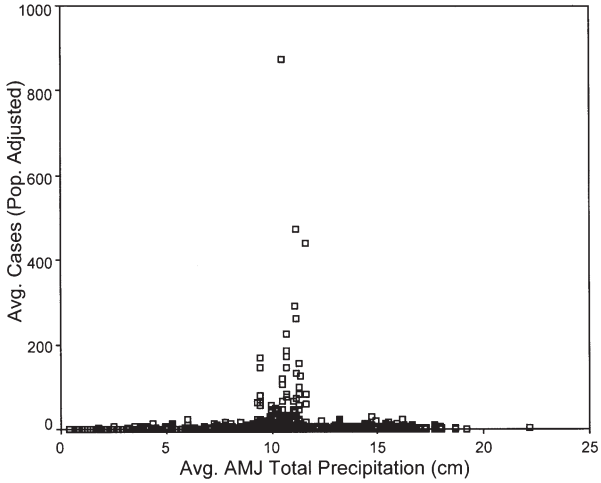

Fig. 2. Average cases by county with corresponding average AMJ precipitation values based on data from 1994 to 1999

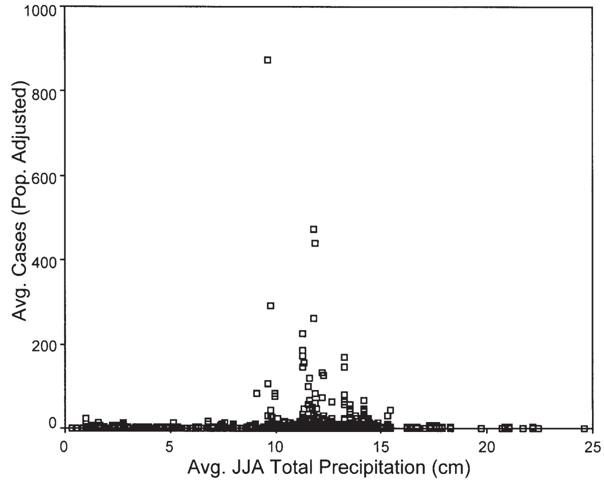

Fig. 3. Average cases by county with corresponding average JJA precipitation values based on data from 1994 to 1999

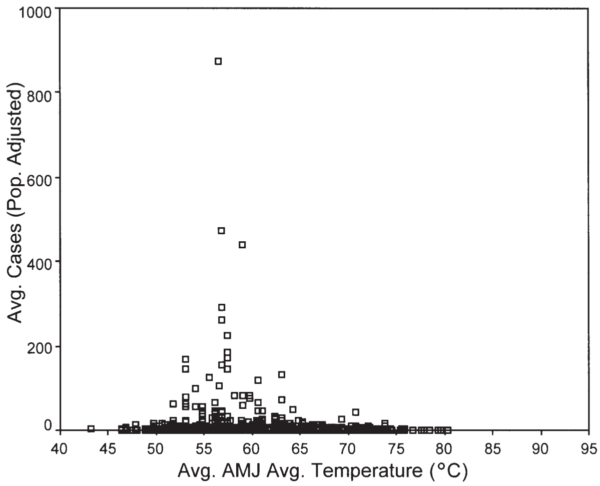

Fig. 4. Average cases by county with corresponding average AMJ temperature values based on data from 1994 to 1999

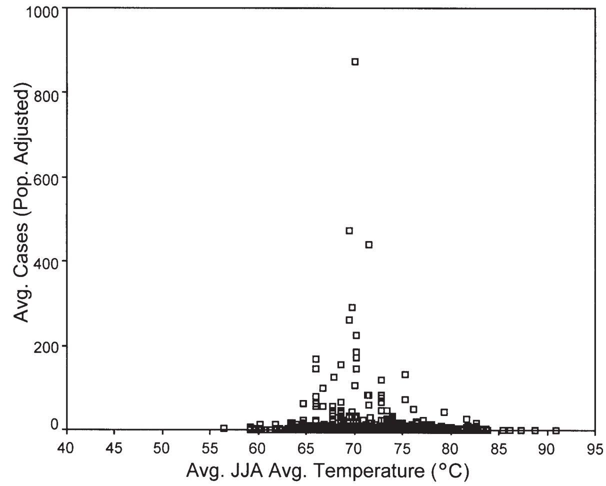

Fig. 5. Average cases by county with corresponding average JJA temperature values based on data from 1994 to 1999

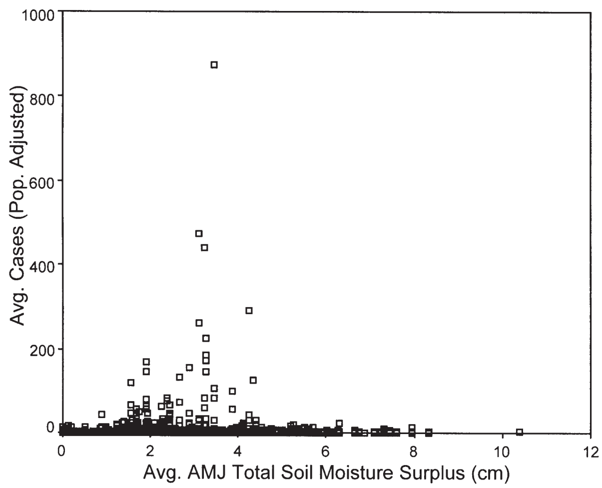

Fig. 6. Average cases by county with corresponding average AMJ soil moisture surplus values based on data from 1994 to 1999

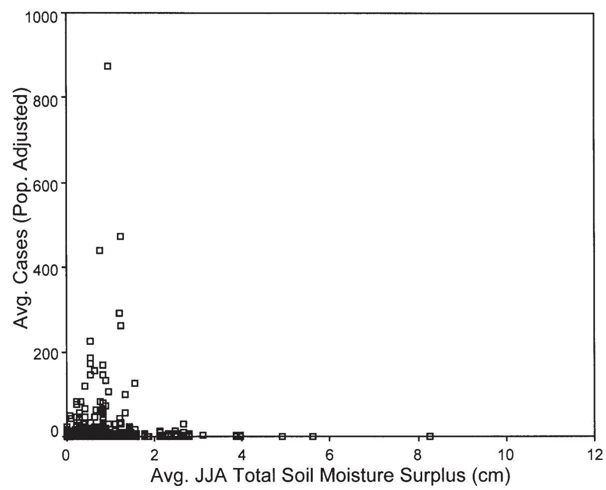

Fig. 7. Average cases by county with corresponding average JJA soil moisture surplus values based on data from 1994 to 1999

ties with higher deficits, a greater proportion have zero or very low average yearly reports of Lyme disease. It is very likely that moist environments in late spring/early summer favor the Lyme disease vector-host system.

The climate and Lyme disease relationship is not a direct cause and effect relationship, but, rather, the climate associated with the months preceding the upcoming Lyme disease season may have a control on the vectors of the disease. The results of this research suggest that the climate during the 3 mo time periods of AMJ and JJA may have some influence on the peak Lyme disease season due to the small degree of spread in the AMJ precipitation plots and JJA soil moisture surplus and temperature plots. Therefore, these 2 time periods and the corresponding climatic variables are singled out for additional analysis.

3.1. 'Climate envelope' method results

To more accurately quantify the range of precipitation, temperature, and soil moisture surplus values that correspond to high cases of Lyme disease, a 'climate envelope' method is used. For this method, Lyme disease reports are first plotted against 2 of the aforementioned climate variables. Initially, these plots were created for all time periods. In order to facilitate comparisons of the meteorological variables across time periods, the *x* and *y* axes were standardized. Only the AMJ and JJA plots are shown here since previous analysis determined that only these time periods have a strong relationship with Lyme disease (Figs. 8 to 11).

The AMJ and JJA climate envelope plots show a clustering of high case counties with similar precipitation, soil moisture surplus, and temperature values within a larger range of climatic values. This indicates that counties with high rates of Lyme disease have similar climate conditions. Comparing the AMJ plots to the JJA plots, the most noticeable difference is seen in Fig. 11 by the tighter cluster of total moisture surplus values for JJA. However, due to the subjectivity in drawing conclusions between precipitation, moisture surplus, and temperature values, the AMJ and JJA ranges of these values for high average disease occurrence (≥100 average annual cases per 100 000 people) counties were calculated as a proportion of the range of that variable (not including counties with <5 average annual cases per 100 000 people).

Results show that for counties with high average annual Lyme disease rates, AMJ precipitation values span 13.8% of the range of precipitation values, AMJ soil moisture surplus values span 34.9%, and AMJ temperature values span 27.6%. Analysis for the JJA climate variables shows that the JJA precipitation values span 21.9% of the range of precipitation values, JJA soil moisture surplus values span 40.1%, and JJA temperature values span 39.3%.

Comparing these ratios for both time periods reveals that the AMJ climate envelope plots have the narrowest cluster of high case counties for all variables. Additionally, out of the 3 AMJ plots, precipitation spans the

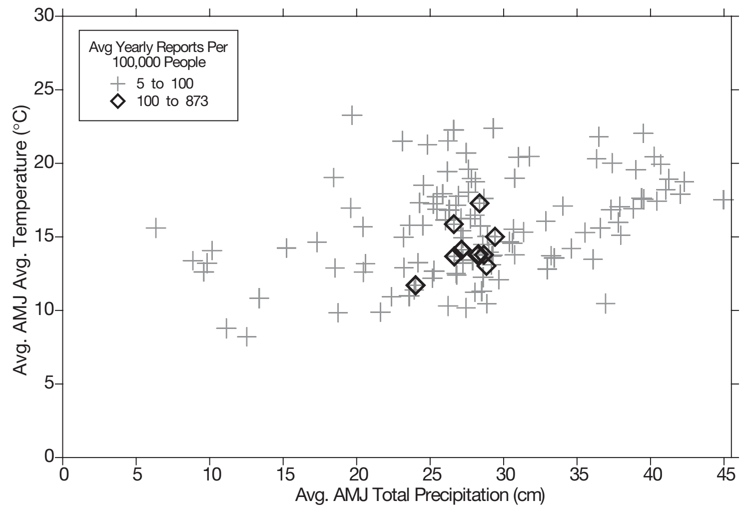

Fig. 8. Average AMJ total precipitation and temperature values with corresponding average yearly reports (1994 to 1999) by county

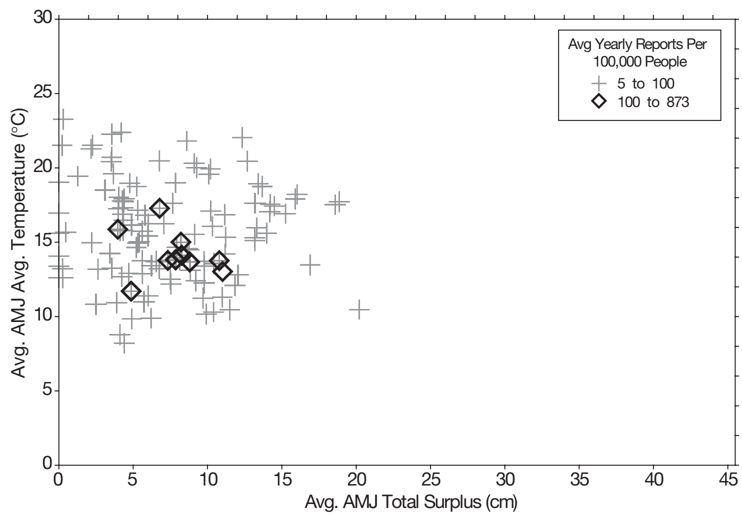

Fig. 9. Average AMJ total soil moisture surplus and temperature values with corresponding average yearly reports (1994 to 1999) by county

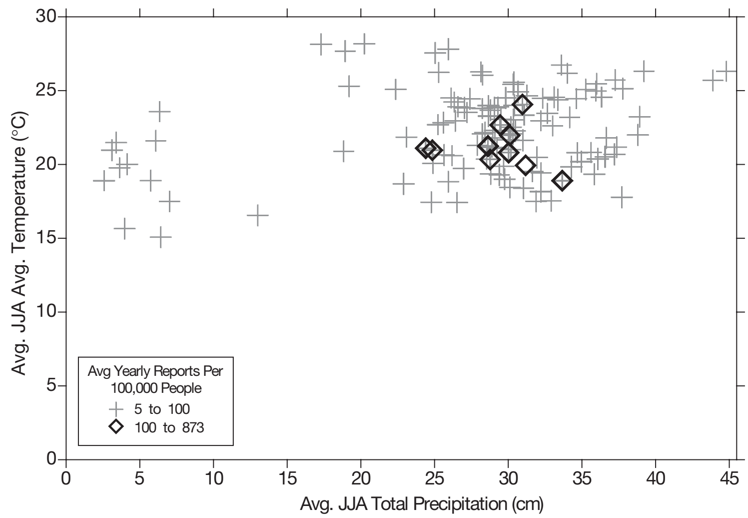

Fig. 10. Average JJA total precipitation and temperature values with corresponding average yearly reports (1994 to 1999) by county

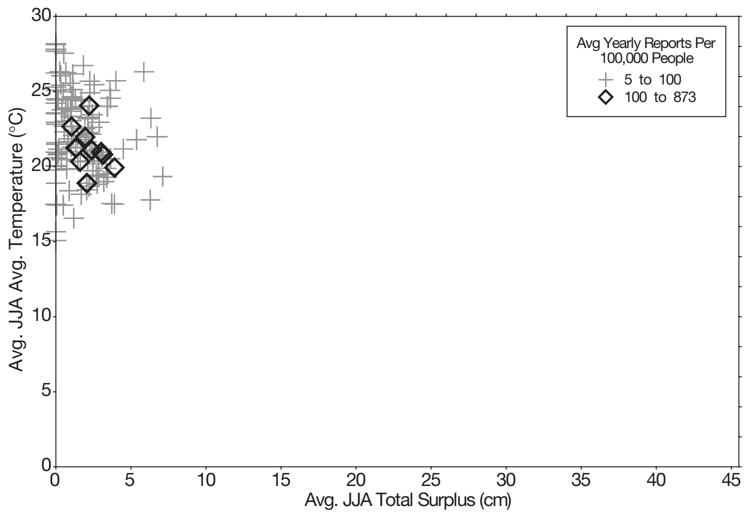

Fig. 11. Average JJA total soil moisture surplus and temperature values with corresponding average yearly reports (1994 to 1999) by county

smallest proportion of the overall range of values. This narrower cluster shows that high reports of Lyme disease occur in counties that for the most part have similar precipitation values. This points to the speculative conclusion that precipitation may have a greater influence on the rates of Lyme disease in a given year than either temperature or moisture surplus values. Regions that are either too dry or too wet do not support rates >100 (average) per year. However, it must be re-stated that all parts of the vector system must be present for Lyme disease to occur.

For the AMJ time period, all of the high rate counties (≥100 average annual cases per 100 000 people) come together to form one main cluster of high reports for Lyme disease. This envelope approach suggests that the disease responds to the climate variables during the 3 mo period immediately 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 & Spielman 1990, Shapiro & Gerber 2000). Therefore, the climate during late spring and early summer may determine the population of infected nymphal ticks that could spread the disease in the summer.

The 'climate envelope' method showed that counties with ≥100 average cases per 100 000 people per year have lower and upper limits of 4.0 and 11.0 cm for their average AMJ soil moisture surplus values, lower and upper limits of 24.0 and 29.4 cm for their average AMJ precipitation values, and lower and upper limits of 11.7 and 17.3°C for their average AMJ temperature values.

This clustering does not rule out the possibility of one or more important confounding effects. As the weather becomes more conducive to outdoor activity in the spring and early summer, the chance that the tick will attach itself to a human should increase greatly. Nevertheless, an infected tick must be present.

3.2. 'Climate envelope' model results

The results of both the single variable and 'climate envelope' method analyses indicate that a useful 3-variable model could be developed. It was found from these analyses that there is a clustering of the climatic variables associated with the endemic counties of Lyme disease. Consequently, the model created takes into account the clustering of climatic variables by only including counties that are in the range of climatic values that are characteristic of the endemic zones and is constructed as follows:

Predicted 'Favorable' Climate = (AMJ Total Precipitation (cm) ≥ 19.69 or ≤ 37.80) + (AMJ Total Soil Moisture Surplus (cm) ≥ 1.28 or ≤ 13.20) + (AMJ Average Temperature (°C) ≥ 10.83 or ≤ 19.44)

A predictive risk map (Fig. 12) shows the counties that met the requirements outlined in the 'climatic envelope' model (average AMJ precipitation range from 19.7 to 37.8 cm, an average AMJ soil moisture surplus range from 1.3 to 13.2 cm, and an average AMJ temperature range from 10.8 and 19.4°C).

The map shows clearly the endemic regions; however, there are counties such as those from Minnesota down through northern Oklahoma, Iowa through Ohio, Michigan, and Virginia down through Georgia that fall in the suitable climate range for Lyme disease to be present, but have <10 average reports per 100 000 people.

On the other hand, there are counties such as those scattered in Missouri, Oklahoma, Texas, Tennessee, and California where the disease exists although their climate characteristics fall out of the 90 % envelope. These counties that do not fall in the climate zone but have reports of the disease consequently have only a small number of average cases (10) per 100 000 people. For these counties with low rates of Lyme disease (but not shown in the climate envelope), it is possible that the disease was not contracted in that county, but elsewhere, possibly in an endemic region. Cases that fall outside of the favorable zone require additional investigation for their uniqueness.

Fig. 12 illustrates that the most suitable climate for Lyme disease occurs in counties throughout the Northeast, Mid-Atlantic to northern Georgia, upper Midwest, Northern to Central Plains, and a few counties in Washington and Oregon. Whether or not these counties have established tick and host populations as well as sufficient human contacts will determine whether or not a county will reach endemic status. This map shows the counties that meet the climate requirements determined by the 'climate envelope' model to support high Lyme disease reports; therefore, for counties within the climate zone with few to no reports, the addition of the other necessary components could cause the disease to thrive.

4. SUMMARY AND CONCLUSIONS

The overall goal of this research was to investigate the spatial distribution of Lyme disease by focusing on the relationship between the geography of Lyme disease reports and observed climate. The spatial cohesion of the disease suggests that it is controlled by other geographic factors, in addition to climate, such as landuse/land cover, and the population of ticks, hosts, and humans.

Using Lyme disease cases as a surrogate to tick density data and human-tick contacts, this research shows that the climate and Lyme disease relationship is not a direct cause-and-effect relationship, but rather, 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.

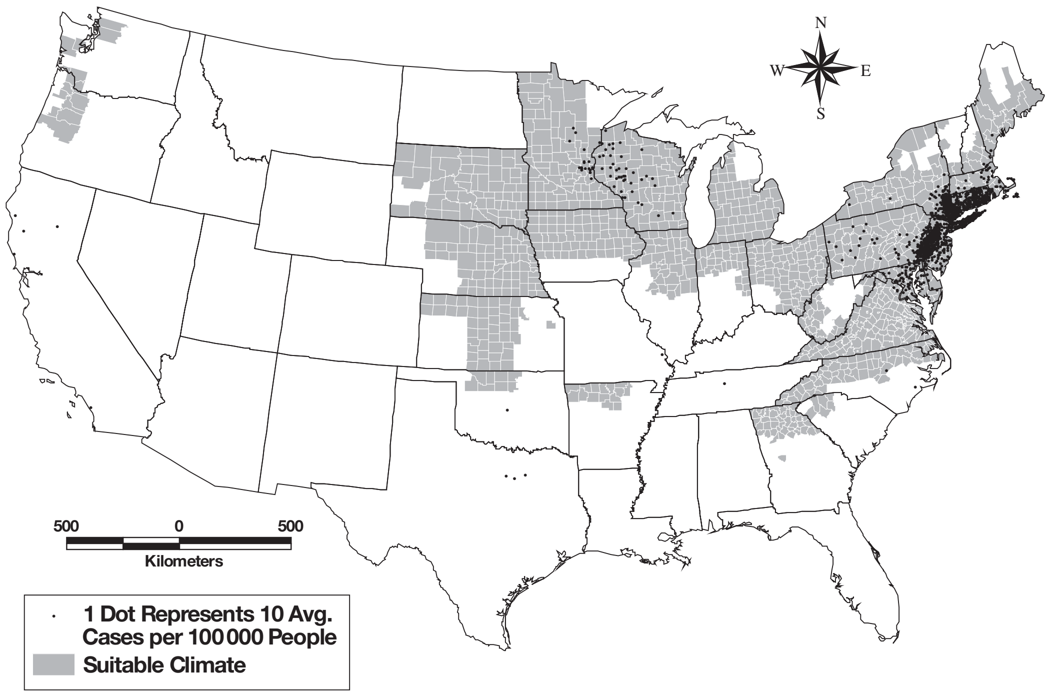

Fig. 12. Potential Climatic Risk Map based on a 'climatic envelope' model. This model is constrained by the average (1994 to 1999) AMJ total precipitation, AMJ average temperature, and AMJ total soil moisture surplus values of the middle 90 % of counties with >10 average cases per 100 000 people. Counties shaded in grey are within the suitable climate range specified by the model

Results suggest that the climate during the 3 mo period AMJ has some influence on Lyme disease the following summer. AMJ is concluded to be the best of the time periods examined because the plots of Lyme disease reports and the climate variables reveal that there is only one core region of climatic values in which the disease occurs. Furthermore it has been found that total precipitation has more control over Lyme disease than either the temperature or soil moisture surplus variables. Therefore, further analysis into the relationship between precipitation characteristics of the tick's habitat and Lyme disease rates may be fundamental in creating a better predictive model for Lyme disease occurrence.

Unfortunately, no predictive model at fine time and spatial scales could be formulated. Nonetheless, the 'climate envelope' model combines the variables to create a predictive risk map that outlines counties with 'favorable' climatic conditions for the disease. 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. Therefore, 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.

A problem for this research was that the optimal data (monthly Lyme disease cases by county and/or monthly *Borrelia burgdorferi*-infected tick density data) needed to research the climate–disease links were not available: therefore, a conclusive predictive model of this relationship could not be formed. Since yearly Lyme disease reports per county were used 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 is conceivable that 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 could be established.

It is recommended that further investigations into the climate–disease link should concentrate on the 3 mo period AMJ. Emphasis should be placed on the moisture characteristics of the county. Previous work has also highlighted the microclimate of the vector's habitat (i.e. leaf litter; Dennis et al. 1998, Lindsay et al. 1999); therefore, future researchers may wish to further 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 combines all the aforementioned elements may be the most efficient way to discover what causes an area to become endemic with Lyme disease, due to the complexity associated with transmitting this disease.

Acknowledgements. The assistance of both N. Hayes (CDC, Division of Vector-borne Infectious Diseases) and R. Jajosky (CDC, Epidemiology Program Office) is gratefully acknowledged. The authors greatly appreciated data supplied by R. Jajosky.

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Editorial responsibility: Otto Kinne, Oldendorf/Luhe, Germany

Submitted: August 18, 2004; Accepted: September 20, 2004
Proofs received from author(s): October 13, 2004