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Original article

Climate change influences on the annual onset of Lyme disease in the United States

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ABSTRACT

Lyme disease is the most commonly reported vector-borne illness in the United States. Lyme disease occurrence is highly seasonal and the annual springtime onset of cases is modulated by meteorological conditions in preceding months. A meteorological-based empirical model for Lyme disease onset week in the United States is driven with downscaled simulations from five global climate models and four greenhouse gas emissions scenarios to project the impacts of 21st century climate change on the annual onset week of Lyme disease. Projections are made individually and collectively for the 12 eastern States where >90% of cases occur. The national average annual onset week of Lyme disease is projected to become 0.4–0.5 weeks earlier for 2025–2040 ($p < 0.05$), and 0.7–1.9 weeks earlier for 2065–2080 ($p < 0.01$), with the largest shifts for scenarios with the highest greenhouse gas emissions. The more southerly mid-Atlantic States exhibit larger shifts (1.0–3.5 weeks) compared to the Northeastern and upper Midwestern States (0.2–2.3 weeks) by 2065–2080. Winter and spring temperature increases primarily cause the earlier onset. Greater spring precipitation and changes in humidity partially counteract the temperature effects. The model does not account for the possibility that abrupt shifts in the life cycle of *Ixodes scapularis*, the primary vector of the Lyme disease spirochete *Borrelia burgdorferi* in the eastern United States, may alter the disease transmission cycle in unforeseen ways. The results suggest 21st century climate change will make environmental conditions suitable for earlier annual onset of Lyme disease cases in the United States with possible implications for the timing of public health interventions.

Introduction

Lyme disease is a multisystem tick-borne bacterial zoonosis that is endemic in parts of North America, Europe and Asia. In the United States, Lyme disease is the most commonly reported vector-borne illness (CDC, 2008), with more than 25,000 Lyme disease cases reported annually since 2007 (CDC, 2014). The majority of Lyme disease cases are reported from Northeastern and north-central States where nymphal *Ixodes scapularis* ticks serve as the primary bridging vectors of the pathogenic bacterium *Borrelia burgdorferi* sensu stricto from zoonotic hosts to humans (CDC, 2008; Piesman, 1989). Lyme disease transmission occurs seasonally, and the majority of human cases report onset of clinical signs of infection during the months of June, July and August, a period that corresponds with exposure to the nymphal life stage of *I. scapularis* (CDC, 2008; Piesman, 1989). The geographic distribution of Lyme disease is focal, and inter-annual variation in case counts and seasonal onset is considerable (Diuk-Wasser et al., 2012; Moore et al., 2014).

Because Lyme disease cases can only occur in areas where humans encounter *B. burgdorferi*-infected ticks, much of the variability in where and when Lyme disease cases occur is attributable to the geographic distribution and seasonal host-seeking patterns of the ticks that serve as vectors of *B. burgdorferi*. Although at local scales host community structure plays a large role in determining the density of infected nymphs (Mather et al., 1989; Ostfeld et al., 2006), at regional scales, temperature, humidity and precipitation are robust predictors of spatial and temporal distributions of *I. scapularis* (Brownstein et al., 2003; Diuk-Wasser et al., 2006, 2010; Estrada-Pena, 2002). These variables have also been associated with

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the geographical and temporal distributions of human cases of Lyme disease in the United States (Ashley and Meentemeyer, 2004; McCabe and Bunnell, 2004; Moore et al., 2014; Ogden et al., 2014; Subak, 2003; Tran and Waller, 2013). Understanding how meteorology impacts the seasonality of Lyme disease case occurrence can aid in targeting limited prevention resources and may shed light on how climate change could affect the seasonal occurrence of the disease (Gray, 2008).

Based on cases reported through the National Notifiable Diseases Surveillance System (NNDSS) from 1992 to 2007, a companion study modeled the timing of the start, peak, duration and end of the Lyme disease season for 12 endemic States in the Northeast, mid-Atlantic and upper Midwest as a function of meteorological variables (Moore et al., 2014). Moore et al. (2014) found significant associations between meteorological variables and the timing of the onset, peak and duration of the Lyme disease season; however, meteorological variables did not predict the end of the season. The strongest associations were found for the onset of the Lyme disease season. Across all States and years, the beginning of the Lyme disease season ranged from week 16–26 of the calendar year, and 60% of the variation was attributable to the geographic and temporal variability of climatic and other environmental factors. The Lyme disease season began earlier in more southerly and coastal States compared with more northerly and inland States. Earlier onset of the Lyme disease season was positively associated with warmer and more humid conditions and lower rainfall amounts during the preceding winter and spring months. Other studies also indicate that warmer and/or more humid conditions are associated with *I. scapularis* characteristics including geographic distribution (Brownstein et al., 2003; Estrada-Pena, 2002; Ogden et al., 2008) and increased density of host-seeking nymphal ticks (Diuk-Wasser et al., 2006, 2010).

Given that climate models project a temperature increase over the United States of 1.5–5.5 °C by the end of the 21st century following a 0.8 °C increase during the 20th century, and that rainfall amounts will likely continue rising over the Northeastern U.S. (USGCRP, 2014) where most Lyme disease cases occur, it is plausible that climate change may affect the annual onset of Lyme disease in forthcoming decades. While previous studies have primarily examined climate change impacts on the geographic distribution, host-seeking phenology and reproductive rate of *Ixodes scapularis* (e.g., Brownstein et al., 2005; Ogden et al., 2006, 2008, 2014; Simon et al., 2014; Levi et al., 2015), none have investigated climate change impacts on the seasonality of human Lyme disease cases in the United States. Here, the national model of Moore et al. (2014) is employed to investigate how projected 21st century climate changes may affect the timing of annual Lyme disease onset in the eastern United States. Development and implementation of such models can aid in determining the magnitude by which climate change may drive shifts in the annual onset of Lyme disease cases, allowing public health officials to gauge whether it will be necessary to adjust future interventions to account for altered seasonality of Lyme disease.

Materials and methods

National Lyme disease model

The best-fit (adjusted $R^2 = 0.785$) national-level model for Lyme disease onset presented in Moore et al. (2014) is:

$$\mathrm{LOW} = 17.56252 - 0.014 \times \mathrm{GDD_{W20}} + 0.945 \times \mathrm{SD_{M5}} + 0.009 \times \mathrm{PRCP_{AW8}} + 0.093 \times \mathrm{DIST} \quad (1)$$

where LOW is Lyme Onset Week (week 1 is defined at the beginning of the calendar year), $\mathrm{GDD_{W20}}$ is the cumulative growing degree days from week 1 to week 20, $\mathrm{SD_{M5}}$ is the mean saturation deficit in mmHg in the 5 weeks before the onset week, $\mathrm{PRCP_{AW8}}$ is the cumulative rainfall in mm from week 8 (approximately the beginning of spring) through the onset week, and DIST is distance in decimal degrees to the Atlantic Ocean coastline from the weighted mean center of each State's total Lyme disease cases. LOW is defined as the week with the maximum percent increase in the number of Lyme disease cases over the previous week. The model indicates that Lyme disease season is expected to begin 1.4 weeks earlier for each additional 100 cumulative GDDs through week 20, about 1 week later for each 1 mmHg increase in saturation deficit (i.e., if humidity decreases with respect to the air temperature), and about 0.9 weeks later for each 100 mm increase in cumulative precipitation between week 8 and the beginning of the Lyme disease season. The time-invariant variable DIST provides a measure of the maritime or continental climate influences in a State. Compared to inland areas, near-coastal areas often have smaller climatic fluctuations due to the moderating influence of the ocean (Bailey, 1980). The model is applied to each State and year separately and then results are aggregated to the regional or national level as needed, or temporally averaged to obtain long-term averages of LOW.

The LOW model was developed using human cases of Lyme disease reported to the Centers for Disease Control and Prevention (CDC) by State and territorial health departments as part of the National Notifiable Disease Surveillance System (NNDSS) from 1992 to 2007 (CDC, 2009). Over 95% of Lyme diseases cases in the United States occurred in 13 States in the east and north-central regions during the study period: Connecticut, Delaware, Maine, Maryland, Massachusetts, Minnesota, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Virginia, and Wisconsin. Reports from Delaware during the study period did not include an illness onset date and Delaware was subsequently excluded from the analysis. Therefore, the national model was developed using Lyme disease case data from the 12 States accounting for >90% of all United States cases reported for 1992–2007. Additional details on case data, model development, and the methodology for defining observed LOW are in Moore et al. (2014).

Climate data

Moore et al. (2014) describe in detail the historical climate data used in the development of the national model. The data are briefly summarized here for clarity. Historical meteorological variables were obtained or derived from the 1/8th degree primary forcing data for Phase 2 of the North American Land Data Assimilation System (NLDAS-2) (Xia et al., 2012). The observation-constrained meteorological variables of NLDAS-2 span 1979-present and are considered to be of suitable quality for use in climate-sensitive human health applications over North America (Luber, 2014). The NLDAS-2 variables were aggregated to the county-level using the Zonal Statistics spatial analysis tool in ArcGIS (Esri, Redlands, CA). State averages of the NLDAS-2 variables were then calculated annually for 1992–2007 using the county-level data, weighted by the percentage of cases in each county during 1992–2007.

Future climate projections were selected from a multi-model ensemble of atmosphere-ocean global climate models (AOGCMs) that participated in phase five of the Coupled Model Intercomparison Experiment (CMIP5) (Taylor et al., 2012). The CMIP5 simulations support the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2013) and the Third National Climate Assessment for the United States (USGCRP, 2014). Specifically used were AOGCM simulations from a database of CMIP5 climate and hydrology projections that have been empirically downscaled with the bias-corrected spatial disaggregation method (Archive Collaborators, 2014; Brekke et al., 2013; Maurer et al., 2007). The empirically downscaled projections were chosen