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Effects of Climate on Variability in Lyme Disease Incidence in the Northeastern United States

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Numbers of reported Lyme disease cases have increased dramatically over the past decade in the northeastern United States, but the year-to-year variability is sizable (average standard deviation ~30% of the mean). An improved understanding of the causes of such variability would aid in prevention and control of the disease, which is transmitted by a spirochete carried in the “black-legged” tick, *Ixodes scapularis*. In this study, the variability in reported Lyme disease incidence between 1993 and 2001 in seven northeastern US states was analyzed as an outcome of weather variability. For all seven states analyzed, significant ($p < 0.05$) positive relations were found for the correlation of early summer disease incidence with the June moisture index (Palmer Hydrological Drought Index) in the region 2 years previously. The correlations may reflect enhanced nymph tick survival in wetter conditions. Few significant relations were found with same-year moisture index, which suggests that moisture has a greater effect on nymph tick survival following the insect’s blood meal than before. In some states, significant correlations were observed related to warmer winter weather a year and a half prior to disease incidence, which may have been due to higher survival and activity levels of the white-footed mouse, the main host for Lyme disease-infected ticks.

climate; environment; humidity; *Ixodes*; Lyme disease; temperature; ticks; weather

Abbreviations: NCDC, National Climatic Data Center; PHDI, Palmer Hydrological Drought Index.

Lyme disease is a common tickborne illness in the United States. The highest incidence is found in New England and the mid-Atlantic region. Numbers of reported Lyme disease cases in the northeastern United States have increased dramatically over the past decade, but the year-to-year variability is large (an average standard deviation of 30 percent of the mean). The variability displays similar patterns in several states with the highest disease incidence (see figure 1).

The disease is transmitted by a spirochete carried in the “black-legged” tick, *Ixodes scapularis*. The life cycle of *I. scapularis* takes 2 years to complete in northern US latitudes. In the US Northeast, variations in the tick life cycle are present, but oviposition (egg-laying) tends to begin in May, and larvae are most abundant in the summer months. Tick larvae feed chiefly on small mammals such as the white-footed mouse, *Peromyscus leucopus*, which can transmit the Lyme disease agent to the tick. Following feeding, the larvae eventually enter a dormant condition for much of the winter. The surviving larvae molt into nymphs in late spring and will seek suitable hosts, including humans, at that time. After the nymphs find a blood meal, they will molt into adults in the autumn, and the surviving adults will lay eggs in the spring if another host—usually a large mammal, such as a deer—has been found.

In the US Northeast, approximately two thirds of human Lyme disease infections are transmitted during the months of June and July by infected nymphs in the second year of the tick life cycle, rather than by larvae or adults. A leading hypothesis relates changes in disease incidence in the US Northeast to periodic changes in acorn production in oak forests. Acorns are a mainstay of the diet of the white-footed mouse, which in the US Northeast is the main host for *I. scapularis* (1, 2). Periodic acorn abundance, known as masting, has been observed to precede local surges in the mouse population the following spring (3).

However, an environmental explanation for regional Lyme disease variability, such as weather, has also been

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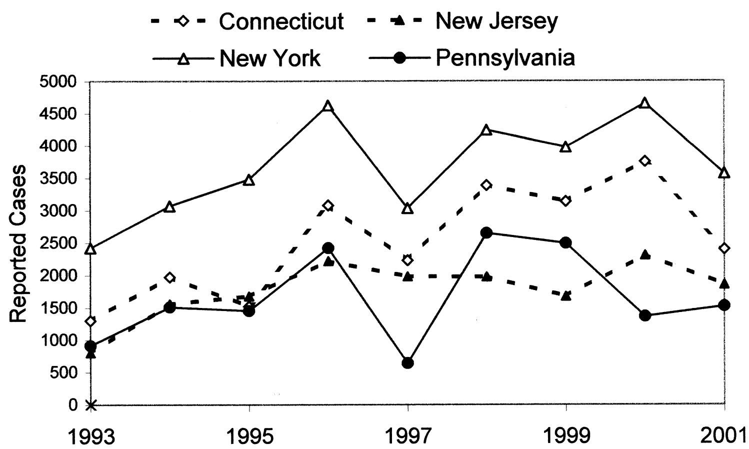

FIGURE 1. Annual incidence of reported Lyme disease in the four northeastern US states with the highest incidence, 1993–2001.

proposed, because similar annual patterns of tick infection rates have been observed in forests dominated by species other than oaks and in regions without forests (4). Ticks require a relatively humid microclimate, such as decomposing plant matter, and soil humidity will affect their survival, particularly during quiescence and dormancy. Tick viability may also be impaired by a scarcity of suitable habitat in circumstances where drier weather has led to lower levels of vegetation available for questing and cover (5). A recent study in northern Illinois found a significant relation between cumulative rainfall and *I. scapularis* density and tick infection rates (6). Previous laboratory research demonstrated the low tolerance of *I. scapularis* to dry weather throughout its life cycle, but particularly in its subadult stages, because the smaller body size is particularly susceptible to water loss (5, 7, 8). Moisture levels during the growing season may also affect the food supply of rodent hosts, which tend to rely on seeds in winter (9).

In addition to drier conditions, cold winter weather may affect Lyme disease incidence because of reduced activity levels among adult ticks seeking their final blood meal (10) and because *P. leucopus* is relatively poorly adapted to cold weather. The white-footed mouse does not enter torpor as readily as other common mouse species, and numbers of white-footed mice tend to decline sharply during winter, especially when food resources are low (11). In the Lyme disease-endemic region of southeastern New York State, sharp drops in the white-footed mouse population following colder winters have been observed in local trapping experiments (3, 12). Analysis of data published by the Institute for Ecosystem Studies (3, 12) suggests that populations of *P. leucopus* trapped in June near Millbrook, New York, were lower following colder winters during the period 1991–1996 compared with the average December, January, and February temperatures during the preceding winter recorded by the National Climatic Data Center, region 0601 (northwestern Connecticut) (R^2 = 0.65, p = 0.053). Long-term studies in the US Midwest indicate that the winter population decline of *P. leucopus* is temporary and that populations tend to recover by the end of the year (9). A decline in the rodent population during winter, however, reduces the probability that tick larvae that hatched in the spring will find a rodent host, become infected, and live to pass on the disease to humans when they enter the nymph stage the following year. Previous studies have shown a strong positive correlation between *P. leucopus* populations in spring and summer and the density of infected nymphs present the following year (12). In turn, nymphal tick abundance has been shown to be directly correlated with Lyme disease incidence in humans (13).

MATERIALS AND METHODS

In this study, broader patterns of Lyme disease incidence, as reported at the state level, were explored in relation to spring/summer moisture and winter temperature using ordinary least-squares regression analysis. The regional analysis was performed using reported Lyme disease incidence in each state as the dependent variable and with the following independent weather variables: summer drought index for the same year (t), summer drought index for the previous year ($t - 1$), and summer drought index for drought occurring 2 years prior to the year of Lyme disease incidence ($t - 2$). Significant correlations with same-year drought (t) would suggest that nymph tick populations decline before the ticks have an opportunity to infect humans. Correlations with previous-year drought ($t - 1$) would provide evidence that larval populations are depleted, affecting nymph populations the following year. Correlations with drought in two earlier periods ($t - 2$) would indicate declines in nymph populations following the blood meal, leading to a failure to complete the 2-year life cycle.

Lyme disease incidence was also considered in a regression equation with winter temperature during the same year (t) and in an equation with winter temperature during the previous year ($t - 1$). A significant relation between Lyme disease incidence and same-year winter temperature (t) would provide some evidence of increased larval winter survival (14, 15). A relation with winter temperature lagged one period ($t - 1$) would support the theory that winter temperature levels affect disease incidence, either through increased adult tick activity or because of greater white-footed mouse survival and activity and consequently higher larval tick infection and survival during the summer months.

These hypotheses were investigated for seven states in the US Northeast with the highest Lyme disease incidence rates—New York, Connecticut, Massachusetts, Rhode Island, Pennsylvania, New Jersey, and Maryland. Together, these states accounted for 85 percent of the approximately 16,000 Lyme disease cases US states reported to the Centers for Disease Control and Prevention for 1999. Annual data on Lyme disease cases and data for the months of highest incidence—June, July, and August—were used in the correlations. Data on the estimated monthly onset of Lyme disease in each state were provided by the states' health departments.

Lyme disease has been under surveillance by the US Centers for Disease Control and Prevention since 1982, but a systematic case definition was only introduced beginning with the 1991 reporting year. Improvements in education and outreach continued after that time, and most state health departments in the Northeast reported an improvement in Lyme disease data quality after the early 1990s. For this analysis, state data on reported annual Lyme disease incidence for the period 1993–2001 provided by each state's department of health were used. Annual numbers of cases reported to the Centers for Disease Control and Prevention as of December 15, 2001, were used for the year 2001, instead of 2001 data from the states' health departments, which were not yet available. For reported onset of Lyme disease by month, only data for the period 1993–2000 were available for all seven states.

In this analysis, summer moisture was represented by Palmer Hydrological Drought Index (PHDI) monthly averages for June, July, and August, the months in which nymphal ticks are most active. The PHDI measures the intensity and duration of long-term drought by considering levels of precipitation, evapo-transpiration, and runoff. Positive values for the index represent moist conditions, and negative values represent drier conditions; for example, severe drought has an index of –3.0 or lower. The influence of winter temperature on disease incidence is tested using average monthly temperatures for the climatologic winter (December, January, and February). Monthly weather data published by the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration were used in all cases. For the smaller states, the NCDC region in the geographic center of the state was selected, and for the others, the NCDC region that most represented the area of Lyme disease concentration was used. The NCDC regions selected included the southern Hudson Valley in New York (NCDC region 5), southeastern Pennsylvania (NCDC region 3), northwestern New Jersey (NCDC region 1), and eastern Maryland (NCDC region 6).

RESULTS

A significant correlation between annual Lyme disease incidence from 1993 to 2001 and summer drought conditions during the same year (t) was evident for only one state. The confidence level of the statistical significance of the correlations was 95 percent ($p < 0.05$) for the state of Rhode Island for the August moisture index and only 90 percent ($p < 0.10$) for Connecticut for the June and July moisture index. The observed relations indicated some evidence of a decline in nymph infection of humans during the year of drier conditions but failed to show a consistent response in all regions. Analysis of drought during the summer prior ($t - 1$) to reported Lyme disease found no significant associations with Lyme disease incidence in any of the seven states.

In four of the seven states examined, significant positive relations were found between annual Lyme disease incidence in 1993–2001 and the summer moisture index from two prior periods ($t - 2$). The relations were significant at $p < 0.05$ for Connecticut, Massachusetts, New York, and Pennsylvania; the relations were correlated at only $p < 0.10$ for Rhode Island and Maryland (see figure 2). (The correlation was weaker for New Jersey, which is not included in figure 2.)

No significant relations were found between annual Lyme disease incidence and same-year winter temperature. Significant positive relations were found in several states between Lyme disease incidence and average winter temperature lagged 1 year. The relations were significant for the states of Massachusetts and Connecticut at $p < 0.05$, but revealed correlations of only $p < 0.10$ for Rhode Island and Maryland and $p > 0.10$ for New York, New Jersey, and Pennsylvania.

The three most important weather variables—PHDI 2 years previously ($t - 2$), winter temperature during the previous year ($t - 1$), and PHDI during the same year (t)—were also correlated with reported Lyme disease onset for each of the summer months. Significant correlations with summer disease onset and same-month drought index were evident for only two states. However, the correlations with June- and July-onset disease incidence and same-month drought index for $t - 2$ were strong and consistent, and over half of the human infections occurred during those months. All of the states' reported disease cases for the month of June were correlated with June PHDI ($t - 2$) at $p < 0.05$, except those for Pennsylvania ($p = 0.053$) (see table 1).

Given the significant correlations of annual disease incidence with June PHDI ($t - 2$), occasionally with winter temperature ($t - 1$), and with June PHDI (t), a multiple regression model was constructed from these three variables (see table 2). The multiple regression model for annual disease incidence and these three variables was found to be significant at $p < 0.05$ for Massachusetts, New York, and Rhode Island and almost significant ($p < 0.10$) for Connecticut. The models explained up to 84 percent (Massachusetts) of the observed variability as adjusted R^2 (see table 2). A two-variable model of June PHDI ($t - 2$) and winter temperature ($t - 1$) was explored for the other states, and results were significant at only $p < 0.10$ for Maryland and Pennsylvania.

Among the three weather variables, significant multicollinearity was not found for the weather variables June PHDI ($t - 2$) and June PHDI (t), but multicollinearity was present for the states of Massachusetts and New Jersey for PHDI ($t - 2$) and winter temperature ($t - 1$) ($r = 0.74$, $p = 0.022$, and $r = 0.68$, $p = 0.045$, respectively) and for New York ($r =$

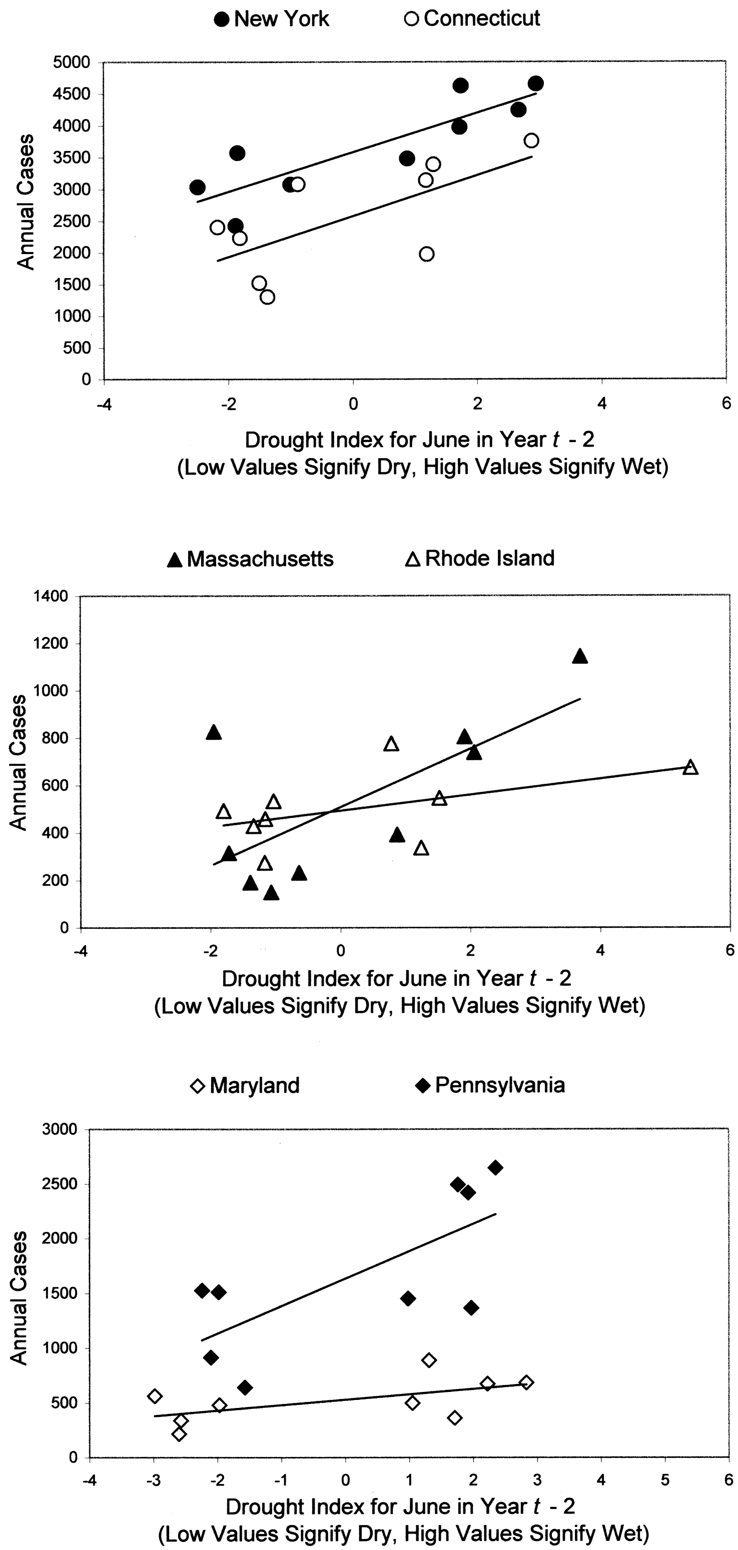

FIGURE 2. Annual incidence of reported Lyme disease according to June moisture levels (Palmer Hydrological Drought Index) 2 years previously ($t - 2$) (8 df) in six northeastern US states, 1993–2001. New York: $R^2 = 0.74$, $p = 0.003$; Connecticut: $R^2 = 0.45$, $p = 0.046$; Massachusetts: $R^2 = 0.49$, $p = 0.036$; Rhode Island: $R^2 = 0.244$, $p = 0.176$ (August Palmer Hydrological Drought Index ($t - 2$): $R^2 = 0.35$, $p = 0.093$); Maryland: $R^2 = 0.45$, $p = 0.068$; Pennsylvania: $R^2 = 0.51$, $p = 0.030$.

TABLE 1. Monthly onset of reported Lyme disease during June, July, and August in relation to weather variables in seven northeastern US states, 1993–2000*

State and statistic	Moisture index (PHDI†) in the same year (*t*) during the same month			Moisture index (PHDI) 2 years previously (*t* – 2) during the same month			Winter temperature during the previous year (*t* – 1)		
	June	July	August	June	July	August	June	July	August
New York									
% of annual cases			**12.7%**	**24.0%**	30.9%	12.7%			**12.7%**
R	—‡	—	**0.86**	**0.92**	0.68	0.66	—	—	**0.74**
p value	—	—	**0.007**	**0.001**	0.064	0.074	—	—	**0.035**
Connecticut									
% of annual cases		**33.5%**	12.9%	**25.4%**	33.5%	12.9%	**25.4%**		
R	—	**0.78**	0.70	**0.85**	0.65	0.68	**0.71**	—	—
p value	—	**0.022**	0.055	**0.008**	0.082	0.062	**0.050**	—	—
Massachusetts									
% of annual cases				**20.8%**	**31.5%**		**20.8%**	**31.5%**	**14.6%**
R	—	—	—	**0.93**	**0.86**	—	**0.71**	**0.73**	**0.74**
p value	—	—	—	**0.001**	**0.007**	—	**0.049**	**0.040**	**0.036**
Rhode Island									
% of annual cases			15.0%	**22.9%**			22.9%		
R	—	—	0.64	**0.77**	—	—	0.63	—	—
p value	—	—	0.089	**0.026**	—	—	0.096	—	—
Pennsylvania									
% of annual cases				27.4%	**25.5%**	**10.3%**			
R	—	—	—	0.70	**0.76**	**0.89**	—	—	—
p value	—	—	—	0.053	**0.029**	**0.003**	—	—	—
New Jersey									
% of annual cases				**30.4%**					
R	—	—	—	**0.71**	—	—	—	—	—
p value	—	—	—	**0.048**	—	—	—	—	—
Maryland									
% of annual cases				**27.9%**					8.7%
R	—	—	—	**0.71**	—	—	—	—	0.63
p value	—	—	—	**0.049**	—	—	—	—	0.096

* All results shown were significant at $p < 0.10$. Results shown in boldface were significant at $p < 0.05$.
† PHDI, Palmer Hydrological Drought Index.
‡ Results were not significant ($p > 0.10$).

0.66, $p = 0.052$). These results call into question the robustness of the winter temperature ($t - 1$) variable in any of the Lyme disease models, given that multicollinearity was identified in Massachusetts and New York—two of the three states where winter temperature ($t - 1$) appeared to be a significant predictor of disease.

DISCUSSION

The present findings relate Lyme disease incidence most strongly to moisture levels 2 years previously. The results support a hypothesis that drought conditions primarily affect nymph tick survival, because a drop in nymph populations following drier weather would reduce adult egg-laying populations and consequently the nymph population level 2 years after the dry summer. The observed lag in disease incidence suggests that the variability is dominated by the vulnerability of ticks that perish under dry conditions after successfully infecting humans and other hosts. The results are consistent with experimental research that found that ticks lose their ability to regulate evaporation and take up water after they begin to feed (5). The correlations also agree with findings obtained on a local scale that higher spring precipitation enhanced the density of nymphs 2 years later (16) and with recent research in Illinois that found that cumulative rainfall through August was positively correlated with the number of larvae collected the following year at the study site (6).

The results are also consistent with a theory that moisture affects rodent host populations, such as that of *P. leucopus*,

TABLE 2. Results from multiple regression models of annual Lyme disease incidence and weather variables in seven northeastern US states, 1993–2001*

State and weather variable	*F*	Significant *F*	R^2	Adjusted R^2
New York				
June PHDI† (*t* – 2)	**9.36**	**0.028**	**0.875**	**0.782**
June PHDI (*t*)				
Winter temperature (*t* – 1)				
Connecticut				
June PHDI (*t* – 2)	5.54	0.066	0.806	0.661
June PHDI (*t*)				
Winter temperature (*t* – 1)				
Massachusetts				
June PHDI (*t* – 2)	**13.03**	**0.016**	**0.907**	**0.838**
June PHDI (*t*)				
Winter temperature (*t* – 1)				
Rhode Island				
August PHDI (*t* – 2)	**6.83**	**0.047**	**0.837**	**0.714**
August PHDI (*t*)				
Winter temperature (*t* – 1)				
New Jersey				
June PHDI (*t* – 2)	—‡	—	—	—
Winter temperature (*t* – 1)				
Pennsylvania				
June PHDI (*t* – 2)	4.73	0.059	0.612	0.482
Winter temperature (*t* – 1)				
Maryland				
June PHDI (*t* – 2)	3.53	0.097	0.541	0.388
Winter temperature (*t* – 1)				

* All results shown were significant at $p < 0.10$. Results shown in boldface were significant at $p < 0.05$.
† PHDI, Palmer Hydrological Drought Index.
‡ Results were not significant ($p > 0.10$).

because less food is produced in the growing season to sustain mice during the critical winter/spring months (6, 9). The current analysis shows that drought may affect the broader pattern of Lyme disease incidence despite the possibility of local host migration from specific study sites. The lack of correlation observed for PHDI (t – 1) and disease incidence undermines an expectation of enhanced larval survival related to moister weather. These results may be consistent with recent findings that ticks in the larval stage may show a more adaptive response to drier weather through quiescence than do nymphs (17).

The lack of correlation observed for same-year moisture (PHDI t) is surprising considering that a higher survival rate would be expected in moister conditions for the unfed nymphs, as well as the fed nymphs. One possible explanation is that people are less likely to spend time outdoors in wetter weather in early summer, so higher tick survival under these conditions is offset by fewer opportunities for humans to encounter ticks. In the United Kingdom, for example, higher Lyme disease incidence has been observed during warmer, drier summers, perhaps because people spend more time outdoors and summer weather tends to be mild (18). However, in the warmer climate of the northeastern United States, drier, hotter conditions may serve to discourage outdoor activities later in the summer. The data show some correspondence in New England between lower Lyme disease incidence and drier conditions in the same month for the months of August and July.

No significant relations were found between annual Lyme disease incidence and same-year winter temperature, which would have provided evidence of increased larval survival related to warmer winter weather (13). The theorized associations between warmer winter weather in the previous year (t – 1) and Lyme disease related to an increase in rodent survival and/or increased adult tick activity over the winter months are tentative. Significant multicollinearity with spring/summer moisture (t – 2) was seen in two out of the three states where winter temperature (t – 1) was found to be a significant predictor of Lyme disease. Further research would be needed to confirm the influence of winter weather on *P. leucopus* survival and transmission of Lyme disease. Preliminary analysis suggests only limited evidence for the other theory—that enhanced adult tick activity in warmer winter weather contributes to a rise in nymph tick populations during the following year. An increase in the activity of adult ticks would be expected to affect winter disease incidence in humans and other hosts, but analysis of disease incidence during the months of December, January, and February, as compared with temperature for each of these months, revealed only a few significant relations. Significant results for onset of disease correlated with same-month temperature for January, February, and December (1993–2000) are as follows: Rhode Island: January, $r = 0.71$, $p = 0.049$; February, $r = 0.83$, $p = 0.011$; New York: December, $r = 0.74$, $p = 0.036$; Connecticut: February, $r = 0.84$, $p = 0.009$. Significant relations were not found for the remaining 17 months tested.

This analysis relied on a limited times series of nine observations on reported Lyme disease incidence. Formal analyses of the quality of the data over time were not available, but some state epidemiologists maintain that reporting has improved over the past decade as awareness by the public and health-care providers has grown. It is also the case for most states that wetter summers and warmer winters predominated in the latter half of the time series. Averaging across the states, the PHDI was greater by about 0.7 and the winters were warmer by about 1°C in the second half of the series compared with the first half. Therefore, the prospect of some positive bias in the correlation results cannot be ruled out, because underreporting in the first half of the series may have coincided with a cooler, drier weather trend. However, although the New York region exhibited the greatest homogeneity in the moisture index, revealing no significant trend, disease incidence in this state was most highly correlated with the moisture index ($t - 2$).

While the results demonstrate that higher Lyme disease incidence is correlated with wetter weather, it might be presumed that excessive rainfall would have an adverse effect on tick populations. For example, a recent study of *I. scapularis* populations at an Illinois site found a steep decline in larval populations in bottomlands following flooding (6). In the series examined for this analysis, only one example of a very high moisture index was available. In this instance, in the state of Rhode Island, the summer PHDI exceeded 4.0 in 1998 and Lyme disease incidence in 2000 was at above-average, but not record, levels. For the other states, higher disease incidence was correlated positively with the highest moisture index, and if a threshold exists after which extreme moisture is negatively correlated, it was not apparent in the limited time series examined.

Summer moisture effects on Lyme disease incidence provide an alternative to the acorn masting theory, which seeks to correlate Lyme disease variability in the US Northeast with changes in the rodent host food supply. More widespread monitoring of acorn production than is currently available would be needed to test the broader implications of masting cycles on Lyme disease incidence. However, in central Massachusetts, where some regional acorn production monitoring has been attempted (3, 19, 20), county Lyme disease data can be examined for elevated disease incidence two summers after major acorn production years. It appears that in the 2 years (1993 and 1995) following the best acorn production years of 1991 and 1993 in central Massachusetts (19), reported disease incidence in central Massachusetts counties was at a record low for the 1990s: at 76 percent and 78 percent below the 1993–2001 mean, respectively. The lack of correspondence between observed acorn production peaks and county-level disease incidence could be due to a lack of synchronization among oak trees, a lack of importance of acorns in the overall mouse food supply, or the fact that other factors, such as those identified in this study, are playing a greater role in disease variability.

The analysis presented may have some implications for the prevention and control of Lyme disease. Currently, some health authorities issue warnings of heightened Lyme disease risk due to recent climatic conditions, that is, a warm winter and a wet spring. The current analysis suggests that warnings of enhanced risk should be revised to take into account knowledge of the lag times between measured climate conditions and human risk. Therefore, warnings of enhanced Lyme disease risk in late spring/early summer would reflect spring moisture conditions that existed 2 years previously. Secondarily, disease risk in late summer is more likely to reflect current soil moisture levels. Regardless of disease variability, authorities can continue to encourage programs for controlling the populations of both the black-legged tick and its main host, the white-footed mouse.

This study has offered evidence of weather-related predictors of Lyme disease incidence that reveals broadly consistent relations in the seven states considered. The relevant changes in weather variables analyzed—wetter springs and summers and warmer winters—are projected to increase in frequency according to recent climate-change scenarios for the northeastern United States. For example, the Global Circulation Models recommended by the Intergovernmental Panel on Climate Change for regional studies project a slight increase in precipitation and an increase in winter temperatures in the US Northeast over the next half century (21). Winter temperatures in the New England region increased by approximately 2°C during the last century (22); and higher survival rates for *P. leucopus* and wetter summers, which improve the survival prospects of nymph ticks, may be contributing factors behind the increasingly high levels of Lyme disease seen in the region.

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