5 VECTOR-BORNE DISEASES

Lead Authors

Charles B. Beard
Centers for Disease Control and Prevention

Rebecca J. Eisen
Centers for Disease Control and Prevention

Contributing Authors

Christopher M. Barker
University of California, Davis

Jada F. Garofalo*
Centers for Disease Control and Prevention

Micah Hahn
Centers for Disease Control and Prevention

Mary Hayden
National Center for Atmospheric Research

Andrew J. Monaghan
National Center for Atmospheric Research

Nicholas H. Ogden
Public Health Agency of Canada

Paul J. Schramm
Centers for Disease Control and Prevention

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**Chapter Coordinator*

5 VECTOR-BORNE DISEASES

Key Findings

Changing Distributions of Vectors and Vector-Borne Diseases

Key Finding 1: Climate change is expected to alter the geographic and seasonal distributions of existing vectors and vector-borne diseases *[Likely, High Confidence]*.

Earlier Tick Activity and Northward Range Expansion

Key Finding 2: Ticks capable of carrying the bacteria that cause Lyme disease and other pathogens will show earlier seasonal activity and a generally northward expansion in response to increasing temperatures associated with climate change *[Likely, High Confidence]*. Longer seasonal activity and expanding geographic range of these ticks will increase the risk of human exposure to ticks *[Likely, Medium Confidence]*.

Changing Mosquito-Borne Disease Dynamics

Key Finding 3: Rising temperatures, changing precipitation patterns, and a higher frequency of some extreme weather events associated with climate change will influence the distribution, abundance, and prevalence of infection in the mosquitoes that transmit West Nile virus and other pathogens by altering habitat availability and mosquito and viral reproduction rates *[Very Likely, High Confidence]*. Alterations in the distribution, abundance, and infection rate of mosquitoes will influence human exposure to bites from infected mosquitoes, which is expected to alter risk for human disease *[Very Likely, Medium Confidence]*.

Emergence of New Vector-Borne Pathogens

Key Finding 4: Vector-borne pathogens are expected to emerge or reemerge due to the interactions of climate factors with many other drivers, such as changing land-use patterns *[Likely, High Confidence]*. The impacts to human disease, however, will be limited by the adaptive capacity of human populations, such as vector control practices or personal protective measures *[Likely, High Confidence]*.

5.1 Introduction

Vector-borne diseases are illnesses that are transmitted by vectors, which include mosquitoes, ticks, and fleas. These vectors can carry infective pathogens such as viruses, bacteria, and protozoa, which can be transferred from one host (carrier) to another. In the United States, there are currently 14 vector-borne diseases that are of national public health concern. These diseases account for a significant number of human illnesses and deaths each year and are required to be reported to the National Notifiable Diseases Surveillance System at the Centers for Disease Control and Prevention (CDC). In 2013, state and local health departments reported 51,258 vector-borne disease cases to the CDC (Table 1).

The seasonality, distribution, and prevalence of vector-borne diseases are influenced significantly by climate factors, primarily high and low temperature extremes and precipitation patterns.[11] Climate change can result in modified weather patterns and an increase in extreme events (see Ch. 1: Introduction) that can affect disease outbreaks by altering biological variables such as vector population size and density, vector survival rates, the relative abundance of disease-carrying animal (zoonotic) reservoir hosts, and pathogen reproduction rates. Collectively, these changes may contribute to an increase in the risk of the pathogen being carried to humans.

Climate change is likely to have both short- and long-term effects on vector-borne disease transmission and infection patterns, affecting both seasonal risk and broad geographic changes in disease occurrence over decades. However, models for predicting the effects of climate change on vector-borne diseases are subject to a high degree of uncertainty, largely due to two factors: 1) vector-borne diseases are maintained in nature in complex transmission cycles that involve vectors, other intermediate zoonotic hosts, and humans; and 2) there are a number of other significant social and environmental drivers of vector-borne disease transmission in addition to cli-

Summary of Reported Case Counts of Notifiable[a] Vector-Borne Diseases in the United States.

Diseases	2013 Reported Cases	Median (range) 2004–2013[b]
Tick-Borne		
Lyme disease	36,307	30,495 (19,804–38,468)
Spotted Fever Rickettsia	3,359	2,255 (1,713–4,470)
Anaplasmosis/Ehrlichiosis	4,551	2,187 (875–4,551)
Babesiosis[b]	1,792	1,128 (940–1,792)
Tularemia	203	136 (93–203)
Powassan	15	7 (1–16)
Mosquito-Borne		
West Nile virus	2,469	1,913 (712–5,673)
Malaria[c]	1,594	1,484 (1,255–1,773)
Dengue[b,c]	843	624 (254–843)
California serogroup viruses	112	78 (55–137)
Eastern equine encephalitis	8	7 (4–21)
St. Louis encephalitis	1	10 (1–13)
Flea-Borne		
Plague	4	4 (2–17)

[a] State Health Departments are required by law to report regular, frequent, and timely information about individual cases to the CDC in order to assist in the prevention and control of diseases. Case counts are summarized based on annual reports of nationally notifiable infectious diseases.[1, 2, 3, 4, 5, 6, 7, 8, 9, 10]

[b] Babesiosis and dengue were added to the list of nationally notifiable diseases in 2011 and 2009, respectively. Median and range values encompass cases reported from 2011 to 2013 for babesiosis and from 2010 to 2013 for dengue.

[c] Primarily acquired outside of the United States and based on travel-related exposures.

Table 1: Vectors and hosts involved in the transmission of these infective pathogens are sensitive to climate change and other environmental factors which, together, affect vector-borne diseases by influencing one or more of the following: vector and host survival, reproduction, development, activity, distribution, and abundance; pathogen development, replication, maintenance, and transmission; geographic range of pathogens, vectors, and hosts; human behavior; and disease outbreak frequency, onset, and distribution.[11]

mate change. For example, while climate variability and climate change both alter the transmission of vector-borne diseases, they will likely interact with many other factors, including how pathogens adapt and change, the availability of hosts, changing ecosystems and land use, demographics, human behavior, and adaptive capacity.[12, 13] These complex interactions make it difficult to predict the effects of climate change on vector-borne diseases.

The risk of introducing exotic pathogens and vectors not currently present in the United States, while likely to occur, is similarly difficult to project quantitatively.[14, 15, 16] In recent years, several important vector-borne pathogens have been introduced or reintroduced into the United States. These include West Nile virus, dengue virus, and chikungunya virus. In the case of the 2009 dengue outbreak in southern Florida, climate change was not responsible for the reintroduction of the virus in this area, which arrived via infected travelers from disease-endemic regions of the Caribbean.[17] In fact, vector populations capable of transmitting dengue have been present for many years throughout much of the southern United States, including Florida.[18] Climate change has the potential to increase human exposure risk or disease transmission following shifts in extended spring and summer seasons as dengue becomes more established in the United States. Climate change effects, however, are difficult to quantify due to the adaptive capacity of a population that may reduce exposure to vector-borne pathogens through such means as air conditioning, screens on windows, vector control and public health practices.

This chapter presents case studies of Lyme disease and West Nile virus infection in relation to weather and climate. Although ticks and mosquitoes transmit multiple infectious pathogens to humans in the United States, Lyme disease and West Nile virus infection are the most commonly reported tick-borne and mosquito-borne diseases in this country (Table 1). In addition, a substantial number of studies have been conducted to elucidate the role of climate in the transmission of these infectious pathogens. These broad findings, together with the areas of uncertainty from these case studies, are generalizable to other vector-borne diseases.[11]

5.2 Lyme Disease

State of the Science

Lyme disease is a tick-borne bacterial disease that is endemic (commonly found) in parts of North America, Europe, and Asia. In the United States, Lyme disease is caused by the bacterium *Borrelia burgdorferi sensu stricto* (*B. burgdorferi;* one of the spiral-shaped bacteria known as spirochetes) and is the most commonly reported vector-borne illness. It is primarily transmitted to humans in the eastern United States by the tick species *Ixodes scapularis* (formerly *I. dammini*), known as blacklegged ticks or deer ticks, and in the far western United States by *I. pacificus*, commonly known as western blacklegged ticks.[19] Illness in humans typically presents with fever, headache, fatigue, and a characteristic skin rash called erythema migrans. If left untreated, infection can spread to joints, the heart, and the nervous system.[20] Since 1991, when standardized surveillance and reporting of Lyme disease began in the United States, case counts have increased steadily.[21] Since 2007, more than 25,000 Lyme disease cases have been reported annually.[22] The geographic distribution of the disease is limited to specific regions in the United States (Figure 2), transmission occurs seasonally, and year-to-year variation in case counts and in seasonal onset is considerable.[20, 21, 23] Each of these observations suggest that geographic location and seasonal climate variability may play a significant role in determining when and where Lyme disease cases are most likely to occur.

Although the reported incidence of Lyme disease is greater in the eastern United States compared with the westernmost United States,[20, 21] in both geographical regions, nymphs (small immature ticks) are believed to be the life stage that is most significant in pathogen transmission from infected hosts (primarily rodents) to humans (Figure 2, Figure 3).[24, 25] Throughout the United States, the majority of human cases report onset of clinical signs of infection during the months of June, July, and August. The summer is a period of parallel increased activity for both blacklegged and western blacklegged ticks in the nymphal life stage (the more infectious stage) and for human recreational activity outdoors.[21, 25]

Infection rates in humans vary significantly from year to year. From 1992 to 2006, variation in case counts of Lyme disease was as high as 57% from one year to the next.[21] Likewise, the precise week of onset of Lyme disease cases across states in the eastern United States, where Lyme disease is endemic, differed by as much as 10 weeks from 1992 to 2007. Much of this variation in timing of disease onset can be explained by geographic region (cases occurred earlier in warmer states in the mid-Atlantic region compared with cooler states in the North); however, the annual variation of disease onset within regions was notable and linked to winter and spring climate variability (see "Annual and Seasonal Variation in Lyme Disease" on page 136).[23]

The geographic and seasonal distributions of Lyme disease case occurrence are driven, in part, by the life cycle of vector ticks (Figure 3). Humans are only exposed to Lyme disease spirochetes (*B. burgdorferi*) in locations where both the vector tick populations and the infection-causing spirochetes are present.[27] Within these locations, the potential for contracting Lyme disease depends on three key factors: 1) tick vector abundance (the density of host-seeking nymphs being particularly important), 2) prevalence of *B. burgdorferi* infection in ticks (the prevalence in nymphs being particularly important), and 3) contact frequency between infected ticks and humans.[28] To varying degrees, climate change can affect all three of these factors.

Climate Change and Health—Lyme Disease

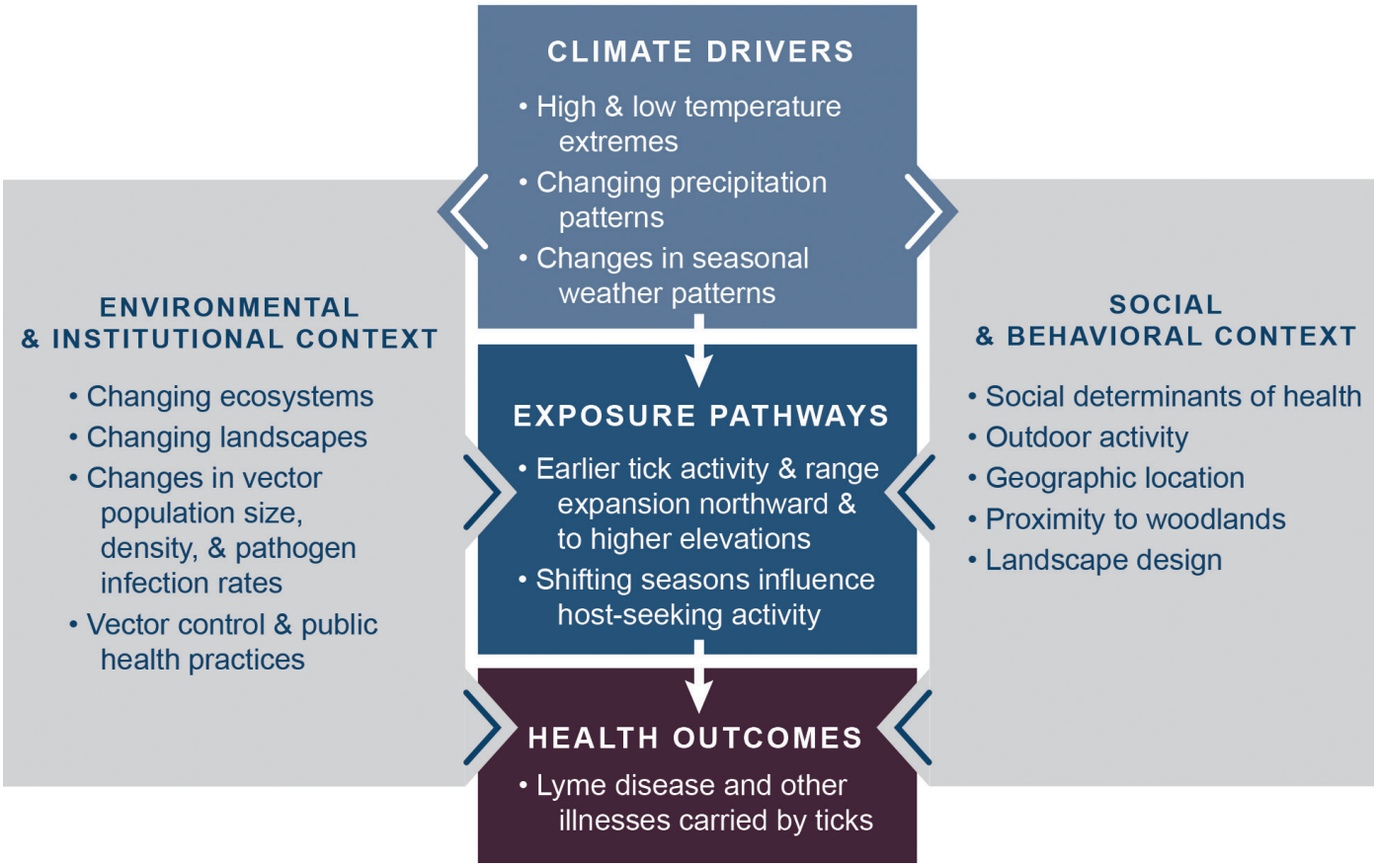


Figure 1: This conceptual diagram illustrates the key pathways by which climate change influences human exposure to Lyme disease and the potential resulting health outcomes (center boxes). These exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box, and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. All of these influencing factors can affect an individual's or a community's vulnerability through changes in exposure, sensitivity, and adaptive capacity and may also be affected by climate change. See Ch. 1: Introduction for more information.

Changes in Lyme Disease Case Report Distribution

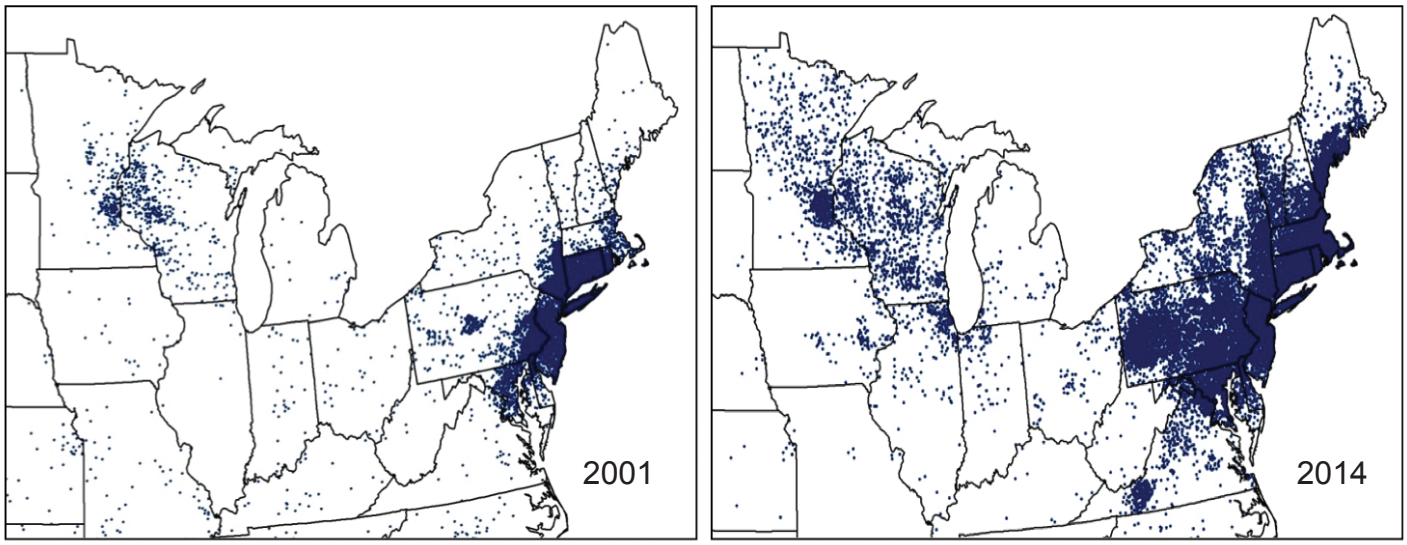


Figure 2: Maps show the reported cases of Lyme disease in 2001 and 2014 for the areas of the country where Lyme disease is most common (the Northeast and Upper Midwest). Both the distribution and the numbers of cases have increased. (Figure source: adapted from CDC 2015)[26]

Life Cycle of Blacklegged Ticks, *Ixodes scapularis*

The seasonal occurrence of Lyme disease cases is related, partially, to the timing of a blood meal (host-seeking activity) of ticks and the three-stage life cycle (larvae, nymph, and adult) of ticks.[48] Increasing temperatures and the accompanying changes in seasonal patterns are expected to result in earlier seasonal tick activity and an expansion in tick habitat range, increasing the risk of human exposure to ticks.

For blacklegged ticks and western blacklegged ticks, spirochete transmission from adult ticks to eggs is rare or does not occur.[49] Instead, immature ticks (larvae and nymphs) acquire infection-causing *B. burgdorferi* spirochetes by feeding on rodents, other small mammals, and birds during the spring and summer months. The spirochetes are maintained throughout the tick life cycle from larva to nymph and from nymph to adult. The spirochetes are primarily passed to humans from nymphs and less frequently by adults.

Prevalence of *B. burgdorferi* infection in nymphal ticks depends in part on the structure of the host community.[50, 51] Larval ticks are more likely to be infected in areas where they feed mostly on animals that can carry and transmit the disease-causing bacteria (such as white-footed mice), compared with areas where they feed mostly on hosts that cannot become infected and thus do not pass on the bacteria (such as certain lizards).

Natural variation in potential for rodents, birds, and reptiles to carry *B. burgdorferi* in the wild leads to large differences in infection rates in nymphal ticks, resulting in considerable geographic variation in the transmission cycles and in the opportunity for humans to contract Lyme disease.[52] Unlike nymphal or larval ticks, adult ticks feed mainly during the cooler months of the year, and primarily on deer, which are resistant to *B. burgdorferi* infection and thus play little role in increasing the abundance of infected ticks in the population. However, deer are important for tick reproduction and therefore influence the abundance of nymphs in subsequent generations.[19]

Life Cycle of Blacklegged Ticks, *Ixodes scapularis*

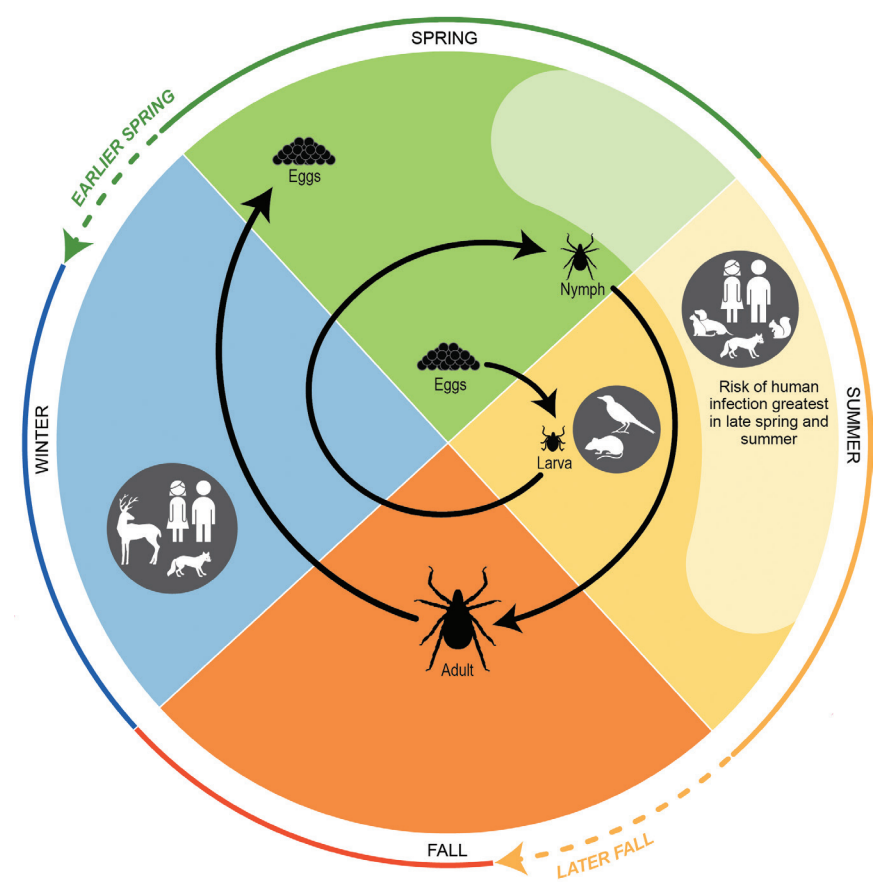


Figure 3: Figure depicts the life cycle of blacklegged ticks, including the phases in which humans can be exposed to Lyme disease, and some of the changes in seasonality expected with climate change. (Figure source: adapted from CDC 2015)[47]

Aside from short periods of time when they are feeding on hosts (less than three weeks of their two- to three-year life cycle), ticks spend most of their lives off of hosts in various natural landscapes (such as woodlands or grasslands) where weather factors including temperature, precipitation, and humidity affect their survival and host-seeking behavior. In general, both low and high temperatures increase tick mortality rates, although increasing humidity can increase their ability to tolerate higher temperatures.[29, 30, 31, 32, 33, 34, 35, 36, 37, 38] Within areas where tick vector populations are present, some studies have demonstrated an association among temperature, humidity, and tick abundance.[39, 40, 41] Factors that are less immediately dependent on climate (for example, landscape and the relative proportions within a community of zoonotic hosts that carry or do not carry Lyme disease-causing bacteria) may be more important in smaller geographic areas.[42, 43] Temperature and humidity also influence the timing of host-seeking activity,[32, 35, 36, 44] and can influence which seasons are of highest risk to the public.

In summary, weather-related variables can determine geographic distributions of ticks and seasonal activity patterns. However, the importance of these weather variables in Lyme disease transmission to humans compared with other important predictors is likely scale-dependent. In general, across the entire country, climate-related variables often play a significant role in determining the occurrence of tick vectors and Lyme disease incidence in the United States (for example, Lyme disease vectors are absent in the arid Intermountain West where climate conditions are not suitable for tick survival). However, within areas where conditions are suitable for tick survival, other variables (for example, landscape and the relative proportions within a community of zoonotic hosts that carry or do not carry Lyme disease-causing bacteria) are more important for determining tick abundance, infection rates in ticks, and ultimately human infection rates.[39, 45, 46]

Observed Trends and Measures of Human Risk

Geographic Distribution of Ticks

Because the presence of tick vectors is required for *B. burgdorferi* transmission to humans, information on where vector tick species live provides basic information on where Lyme disease risk occurs. Minimum temperature appears to be a key variable in defining the geographic distribution of blacklegged ticks.[39, 45, 53] Low minimum temperatures in winter may lead to environmental conditions that are unsuitable for tick population survival. The probability of a given geographic area being suitable for tick populations increases as minimum temperature rises.[45] In the case of the observed northward range expansion of blacklegged ticks into Canada, higher temperatures appear to be a key factor affecting where, and how fast, ticks are colonizing new localities.[54, 55, 56, 57, 58]

In the eastern United States, Lyme disease is transmitted to humans primarily by blacklegged (deer) ticks.

Maximum temperatures also significantly affect where blacklegged ticks live.[39, 45] Higher temperatures increase tick development and hatching rates, but reduce tick survival and egg-laying (reproduction) success.[30]

Declines in rainfall amount and humidity are also important in limiting the geographic distribution of blacklegged ticks. Ticks are more likely to reside in moister areas because increased humidity can increase tick survival.[35, 38, 39, 45, 53, 55]

Geographic Distribution of Infected Ticks

Climate variables have been shown to be strong predictors of geographic locations in which blacklegged ticks reside, but less important for determining how many nymphs live in a given area or what proportion of those ticks is infected.[39, 40] The presence of uninfected nymphs and infected nymphs can vary widely over small geographic areas experiencing similar temperature and humidity conditions, which supports the hypothesis that factors other than weather play a significant role in determining nymph survival and infection rates.[37, 39, 40, 41, 44] Additional studies that modeled nymphal density within small portions of the blacklegged tick range (north-central states and Hudson River Valley, NY), and modeling studies that include climate and other non-biological variables indicate only a weak relationship to nymphal density.[59, 60] Nonetheless, climate variables can be used to model nymphal density in some instances. For example, in a single county in northern coastal California with strong climate gradients, warmer areas with less variation between maximum and minimum monthly water vapor in the air were characteristic of areas with elevated concentrations of infected nymphs.[41] However, it is likely that differences in animal host community structure, which vary with climatic conditions (for example, relative abundances of hosts that carry or do not carry Lyme disease-causing bacteria), influenced the concentration of infected nymphs.[37, 61]

Geographic Distribution of Lyme Disease

Though there are links between climate and tick distribution, studies that look for links between weather and geographical differences in human infection rates do not show a clear or consistent link between temperature and Lyme disease incidence.[46, 62, 63]

Annual and Seasonal Variation in Lyme Disease

Temperature and precipitation both influence the host-seeking activity of ticks, which may result in year-to-year variation in the number of new Lyme disease cases and the timing of the season in which Lyme disease infections occur. However, identified associations between precipitation and Lyme disease incidence, or temperature and Lyme disease incidence, are limited or weak.[64, 65] Overall, the association between summer moisture and Lyme disease infection rates in humans remains inconsistent across studies.

The peak period when ticks are seeking hosts starts earlier in the warmer, more southern, states than in northern states.[44] Correspondingly, the onset of human Lyme disease cases occurs earlier as the growing degree days (a measurement of temperature thresholds that must be met for biological processes to occur) increases, yet, the timing of the end of the Lyme disease season does not appear to be determined by weather-related variables.[23] Rather, the number of potential carriers (for example, deer, birds, and humans) likely influences the timing of the end of the Lyme disease season.

The effects of temperature and humidity or precipitation on the seasonal activity patterns of nymphal western blacklegged ticks is more certain than the impacts of these factors on the timing of Lyme disease case occurrence.[36, 37] Peak nymphal activity is generally reached earlier in hotter and drier areas, but lasts for shorter durations. Host-seeking activity ceases earlier in the season in cooler and more humid conditions. The density of nymphal western blacklegged ticks in north-coastal California consistently begins to decline when average daily maximum temperatures are between 70°F (21°C) and 73.5°F (23°C), and when average maximum daily relative humidity decreases below 83%–85%.[36, 37]

Projected Impacts

Warmer winter and spring temperatures are projected to lead to earlier annual onset of Lyme disease cases in the eastern United States (see "Research Highlight" below) and in an earlier onset of nymphal host-seeking behavior.[66] Limited research shows that the geographic distribution of blacklegged ticks is expected to expand to higher latitudes and elevations in the future and retract in the southern United States.[67] Declines in subfreezing temperatures at higher latitudes may be responsible for improved survival of ticks. In many woodlands, ticks can find refuge from far-subzero winter air temperatures in the surface layers of the soil.[68, 69] However, a possibly important impact of climate change will be acceleration of the tick life cycles due to higher temperatures during the spring, summer, and autumn, which would increase the likelihood that ticks survive to reproduce.[58, 70] This prediction is consistent with recent observations of the spread of *I. scapularis* in Canada.[55, 71]

Research Highlight: Lyme Disease

Importance: Lyme disease occurrence is highly seasonal. The annual springtime onset of Lyme disease cases is regulated by climate variability in preceding months. Until now, the possible effects of climate change on the timing of Lyme disease infection in humans early and late in the 21st century have not been addressed for the United States, where Lyme disease is the most commonly reported vector-borne disease.

Objectives: Examine the potential impacts of 21st century climate change on the timing of the beginning of the annual Lyme disease season (annual onset week) in the eastern United States.

Methods: Downscaled future climate projections for four greenhouse gas (GHG) concentration trajectories from five atmosphere–ocean global climate models (AOGCMs) are input to the national-level empirical model of Moore et al. (2014)[23] to simulate the potential impact of 21st century climate change on the annual onset week of Lyme disease in the United States.[23] The four GHG trajectories in order of lowest to highest concentrations are RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (see Appendix 1: Technical Support Document).

Results: Historical and future projections for the beginning of the Lyme disease season are shown in Figure 4. Historical results are for the period 1992–2007, where the national-average peak onset date for Lyme disease occurs on week 21.2 of the calendar year (mid-May). Future projections are for two time periods: 1) 2025–2040 and 2) 2065–2080. On average, the start of the Lyme disease season is projected to arrive a few days earlier for 2025–2040 (0.4–0.5 weeks), and approximately one to two weeks earlier for 2065–2080 (0.7–1.9 weeks) depending on the GHG trajectory. Winter and spring temperature increases are primarily responsible for the earlier peak onset of Lyme disease infections.

Research Highlight: Lyme Disease, continued

Conclusions: Results demonstrate that 21st century climate change will lead to 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. The end of the Lyme disease season is not strongly affected by climate variables; therefore, conclusions about the duration of the transmission season or changes in the annual number of new Lyme disease cases cannot be drawn from this study.

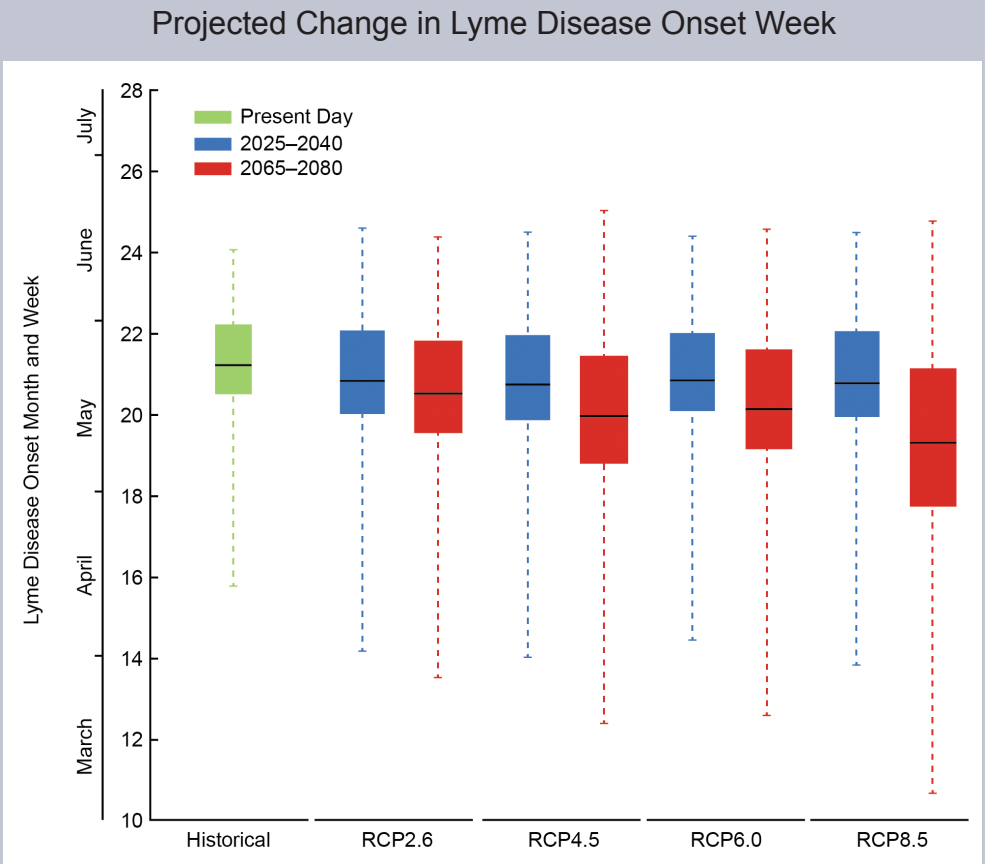


Figure 4: Box plots comparing the distributions of the national-level historical observed data for annual Lyme disease onset week (1992–2007 in green) with the distributions of AOGCM multi-model mean projections of Lyme onset week for each of four Representative Concentration Pathways (RCP2.6, 4.5, 6.0, and 8.5) and two future time periods (2025–2040 in blue, 2065–2080 in red). Each box plot shows the values of Lyme disease onset week for the maximum (top of dashed line), 75th percentile (top of box), average (line through box), 25th percentile (bottom of box), and minimum (bottom of dashed line) of the distribution. All distributions are comprised of values for 12 eastern states and 16 years (N = 192). Additional details can be found in Monaghan et al. (2015). (Figure source: adapted from Monaghan et al. 2015).[72]

To project accurately the changes in Lyme disease risk in humans based on climate variability, long-term data collection on tick vector abundance and human infection case counts are needed to better understand the relationships between changing climate conditions, tick vector abundance, and Lyme disease case occurrence.

5.3 West Nile Virus

State of the Science

West Nile virus (WNV) is the leading cause of mosquito-borne disease in the United States. From 1999 to 2013, a total of 39,557 cases of WNV disease were reported in the United States.[73] Annual variation is substantial, both in terms of case counts and the geographic distribution of cases of human infection (Figure 5).[73] Since the late summer of 1999, when an outbreak of WNV first occurred in New York City,[74] human WNV cases have occurred in the United States every year. After the introduction of the virus to the United States, WNV spread westward, and by 2004 WNV activity was reported throughout the contiguous United States.[75, 76] Annual human WNV incidence remained stable through 2007, decreased substantially through 2011, and increased again in 2012, raising questions about the factors driving year-to-year variation in disease transmission.[75] The locations of annual WNV outbreaks vary, but several states have reported consistently high rates of disease over the years, including Arizona, California, Colorado, Idaho, Illinois, Louisiana, New York, North Dakota, South Dakota, and Texas.[73, 75]

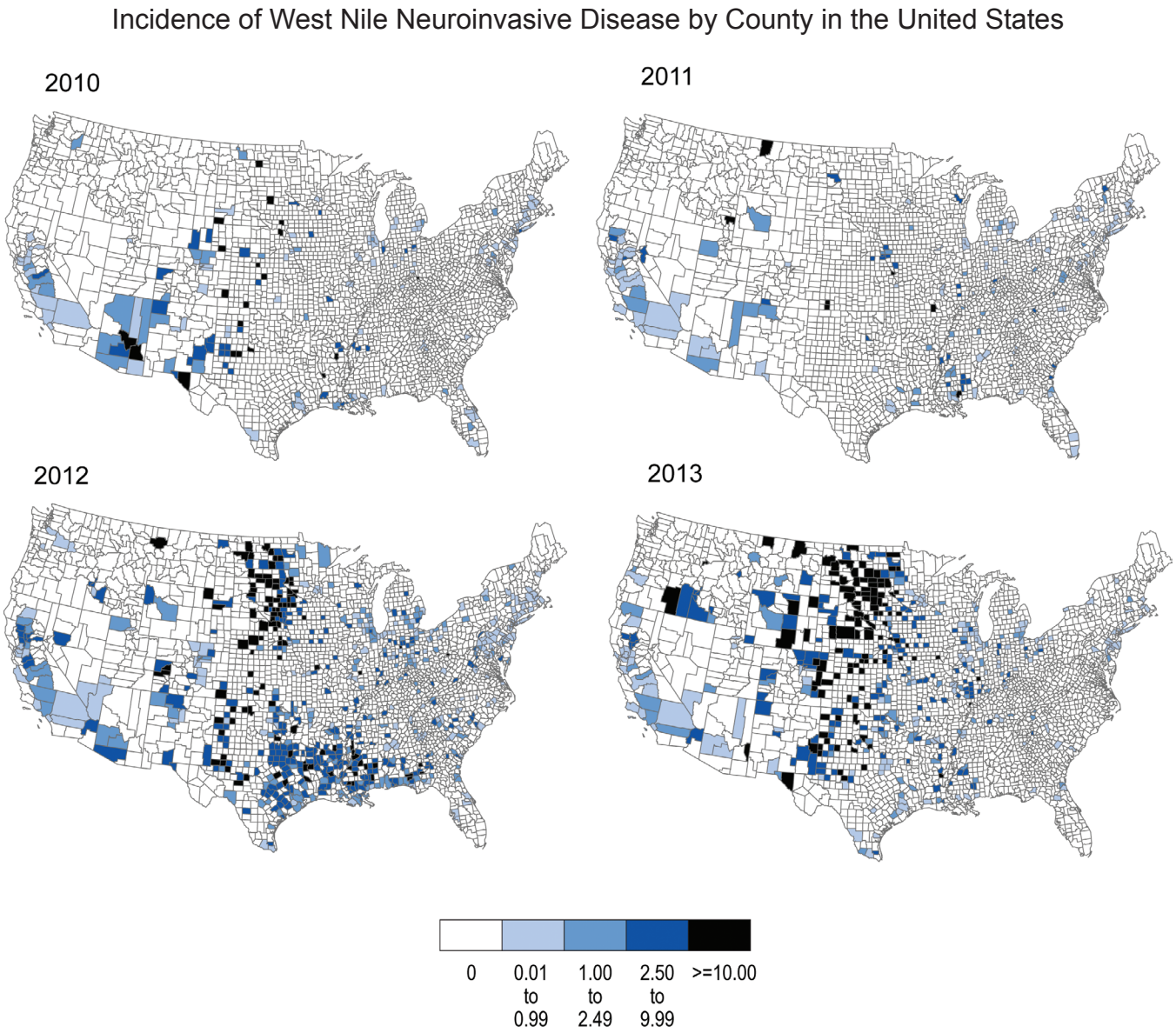


Figure 5: Maps show the incidence of West Nile neuroinvasive disease in the United States for 2010 through 2013. Shown as cases per 100,000 people. (Data source: CDC 2014)[73]

The majority (70% to 80%) of people infected with WNV do not show symptoms of the disease. Of those infected, 20% to 30% develop acute systemic febrile illness, which may include headache, myalgias (muscle pains), rash, or gastrointestinal symptoms; fewer than 1% experience neuroinvasive disease, which may include meningitis (inflammation around the brain and spinal cord), encephalitis (inflammation of the brain), or myelitis (inflammation of the spinal cord) (see "5.4 Populations of Concern" on page 142).[77] Because most infected persons are asymptomatic (showing no symptoms), there is significant under-reporting of cases.[78, 79, 80] More than three million people were estimated to be infected with WNV in the United States from 1999 to 2010, resulting in about 780,000 illnesses.[77] However, only about 30,700 cases were reported during the same time span.[73]

West Nile virus is maintained in transmission cycles between birds (the natural hosts of the virus) and mosquitoes (Figure 6). The number of birds and mosquitoes infected with WNV increases as mosquitoes pass the virus from bird to bird starting in late winter or spring. Human infections can occur from a bite of a mosquito that has previously bitten an infected bird.[81] Humans do not pass on the virus to biting mosquitoes because they do not have sufficient concentrations of the virus in their bloodstreams.[82, 83] In rare instances, WNV can be transmitted through blood transfusions or organ transplants.[82, 84] Peak transmission of WNV to humans in the United States typically occurs between June and September, coinciding with the summer season when mosquitoes are most active and temperatures are highest.[85]

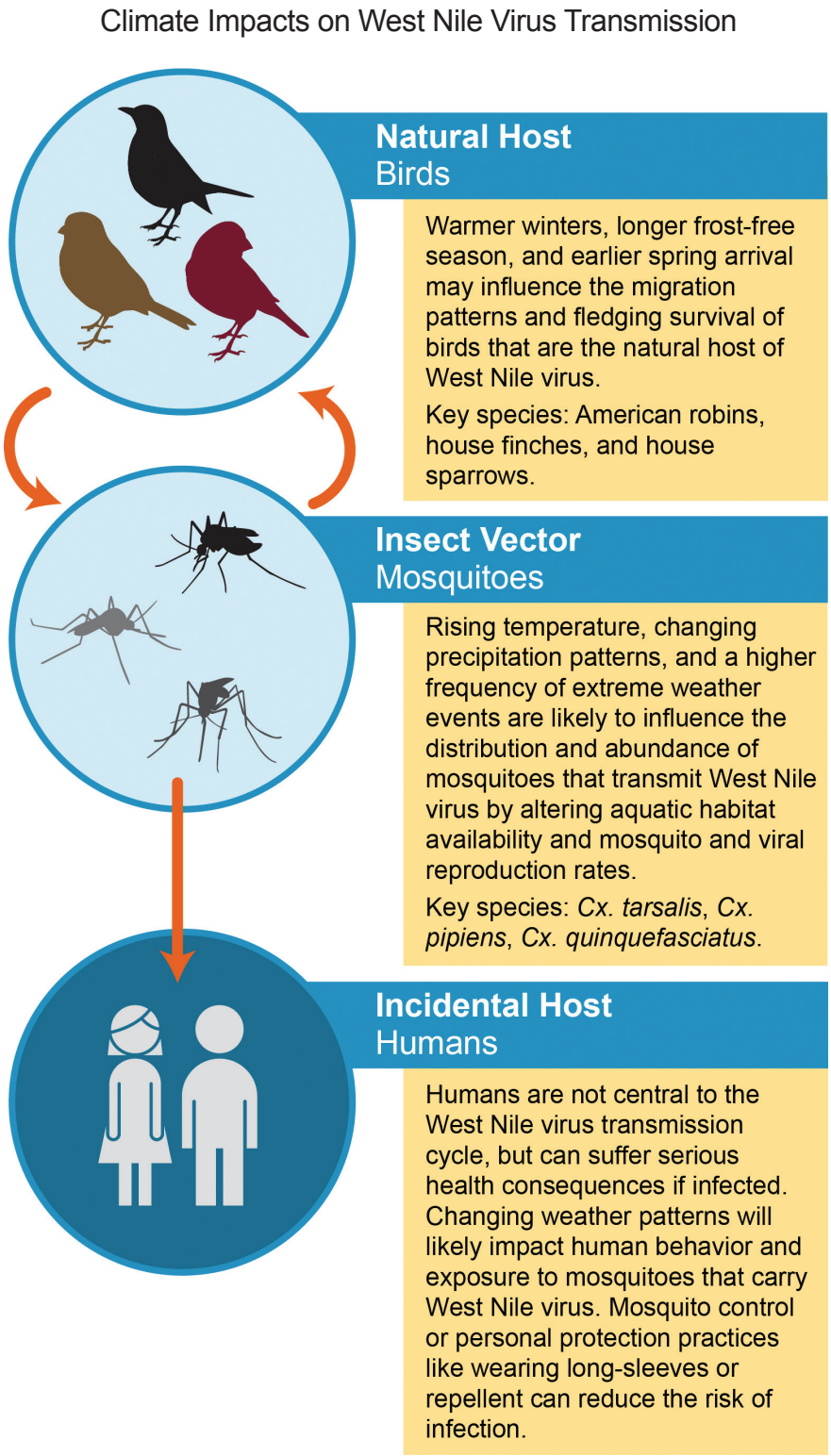


Figure 6: Climate Impacts on West Nile Virus Transmission

Observed Impacts and Indicators

Mosquito vectors and bird hosts are required for WNV to persist, and the dynamics of both are strongly affected by climate in a number of ways. Geographical variation in average climate constrains the ranges of both vectors and hosts, while shorter-term climate variability affects many aspects of vector and host population dynamics. Unlike ticks, mosquitoes have short life cycles and respond more quickly to climate drivers over relatively short timescales of days to weeks. Impacts on bird abundance are often realized over longer timescales of months to years due to impacts on annual reproduction and migration cycles.

WNV has been detected in 65 mosquito species and more than 300 bird species in the United States,[85] although only a relatively small number of these species contribute substantively to human infections. Three *Culex* (*Cx.*) mosquito species are the primary vectors of the virus in different regions of the continental United States, and differences in their preferred breeding habitats mean that climate change will likely impact human WNV disease risk differently across these regions (Figure 5). Bird species that contribute to WNV transmission include those that develop sufficient viral concentrations in their blood to transmit the virus to feeding mosquitoes.[86, 87] As with mosquitoes, the bird species involved in the transmission cycle are likely to respond differently to climate change, increasing the complexity of projecting future WNV risk.

Impacts of Climate and Weather

Climate, or the long-term average weather, is important for defining WNV's transmission range limits because extreme conditions—too cold, hot, wet, or dry—can alter mosquito and bird habitat availability, increase mortality in mosquitoes or birds, and/or disrupt viral transmission. WNV is an invasive pathogen that was first detected in the United States just over 15 years ago, which is long enough to observe responses of WNV to key weather variables, but not long enough to observe responses to climate change trends.

Climate change has already begun to cause shifts in bird breeding and migration patterns, but it is unknown how these changes may affect West Nile virus transmission.

Climate change may influence mosquito survival rates through changes in season length, although mosquitoes are also able to adapt to changing conditions. For example, mosquitoes that transmit WNV are limited to latitudes and altitudes where winters are short enough for them to survive.[88] However, newly emerged adult female mosquitoes have some ability to survive cold temperatures by entering a reproductive arrest called diapause as temperatures begin to cool and days grow shorter in late summer.[89, 90] These females will not seek a blood meal until temperatures begin to warm the following year. Even during diapause, very harsh winters may reduce mosquito populations, as temperatures near freezing have been shown to kill diapausing *Cx. tarsalis*.[91]

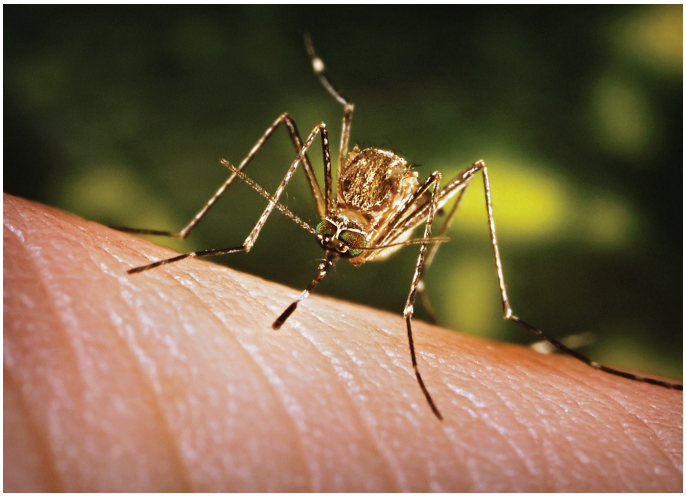
Birds such as the house finch are the natural host of West Nile virus.

During the warmer parts of the year, *Culex* mosquitoes must have aquatic habitat available on a nearly continuous basis because their eggs hatch within a few days after they are laid and need moisture to remain viable. The breeding habitats of WNV vectors vary by species, ranging from fresh, sunlit water found in irrigated crops and wetlands preferred by *Cx. tarsalis* to stagnant, organically enriched water sources, such as urban storm drains, unmaintained swimming pools, or backyard containers, used by *Cx. pipiens* and *Cx. quinquefasciatus*.[92, 93, 94]

WNV has become endemic within a wide range of climates in the United States, but there is substantial geographic variation in the intensity of virus transmission. Part of this geographic variation can be attributed to the abundance and distributions of suitable bird hosts.[95] Important hosts, such as robins, migrate annually between summer breeding grounds and winter foraging areas.[86, 96] Migrating birds have shown potential as a vehicle for long-range virus movement.[97, 98] Although the timing of migration is driven by climate, the impact of climate change-driven migration changes on WNV transmission have not yet been documented by scientists. Climate change has already begun to cause shifts in bird breeding and migration patterns,[99] but it is unknown how these changes may affect WNV transmission.

Temperature is the most studied climate driver of the dynamics of WNV transmission. It is clear that warm temperatures accelerate virtually all of the biological processes that affect transmission: accelerating the mosquito life cycle,[100, 101, 102, 103, 104] increasing the mosquito biting rates that determine the frequency of contact between mosquitoes and hosts,[105, 106] and increasing viral replication rates inside the mosquito that decrease the time needed for a blood-fed mosquito to be able to pass on the virus.[107, 108, 109] These relationships between increasing temperatures and the biological processes that affect WNV transmission suggest a subsequent increase in risk of human disease.[110, 111, 112, 113] However, results from models have suggested that extreme high temperatures combined with decreased precipitation may decrease mosquito populations.[114]

Precipitation can create aquatic breeding sites for WNV vectors,[115, 116] and in some areas snowpack increases the amount of stored water available for urban or agricultural systems, which provide important habitat for WNV vectors,[117, 118] although effects depend on human water management



Humans can be infected from a bite of a mosquito that has previously bitten an infected bird.

decisions and vary spatially.[101] Droughts have been associated with increased WNV activity, but the association between decreased precipitation and WNV depends on location and the particular sequence of drought and wetting that precedes the WNV transmission season.[119, 120, 121, 122]

The impact of year-to-year changes in precipitation on mosquito populations varies among the regions of the United States and is affected by the typical climate of the area as well as other non-climate factors, such as land use or water infrastructure and management practices. In the northern Great Plains—a hotspot for WNV activity—increased precipitation has been shown to lead to higher *Cx. tarsalis* abundance a few weeks later.[116] In contrast, in the typically wet Pacific Northwest, weekly precipitation was found to be unrelated to subsequent mosquito abundance.[123] In urban areas, larvae (aquatic immature mosquitoes) may be washed out of their underground breeding habitats by heavy rainfall events, making drier conditions more favorable for WNV transmission.[110, 124, 125] In rural areas or drier regions, increased precipitation or agricultural irrigation may provide the moisture necessary for the development of breeding habitats.[121]

Impacts of Long-Term Climate Trends

The relatively short period of WNV's transmission in the United States prevents direct observation of the impacts of long-term climate trends on WNV incidence. However, despite the short history of WNV in the United States, there are some lessons to be learned from other mosquito-borne diseases with longer histories in the United States.

Western equine encephalomyelitis virus (WEEV) and St. Louis encephalitis virus (SLEV) were first identified in the 1930s and have been circulating in the United States since that time. Like WNV, both viruses are transmitted primarily by *Culex* mosquitoes and are climate-sensitive. WEEV outbreaks were associated with wet springs followed by warm summers.[118, 126] Outbreaks of SLEV were associated with hot, dry periods when urban mosquito production increased due to stagnation of water in underground systems or when cycles of drought and wetting set up more complex transmission dynamics.[127, 128]

Despite climatic warming that would be expected to favor increased WEEV and SLEV transmission, both viruses have had sharply diminished incidence during the past 30 to 40 years.[129, 130] Although the exact reason for this decline is unknown, it is likely a result of non-climate factors, such as changes in human behavior or undetected aspects of viral evolution. Several other mosquito-borne pathogens, such as chikungunya and dengue, have grown in importance as global health threats during recent decades; however, a link to climate change induced disease expansion in the United States has not yet been confirmed. These examples demonstrate the variable impact that climate change can have on different mosquito-borne diseases and help to explain why the direction of future trends in risk for WNV remain unclear.

Projected Impacts

Given WNV's relatively short history in the United States, the described geographic variation in climate responses, and the complexity of transmission cycles, projecting the future distribution of WNV under climate change remains a challenge. Despite the growing body of work examining the connections between WNV and weather, climate-based seasonal forecasts of WNV outbreak risk are not yet available at a national scale. Forecasting the annual presence of WNV disease on the basis of climate and other ecological factors has been attempted for U.S. counties, with general agreement between modeled expectations and observed data, but more quantitative predictions of disease incidence or the risk for human exposure are needed.[131]

Longer-term projections of WNV under climate change scenarios are also rare. WNV is projected to increase in much of the northern and southeastern United States due to rising temperatures and declining precipitation, respectively, with the poten-

tial for decreased occurrence across the central United States.[132] Future projections show that the season when mosquitoes are most abundant will begin earlier and end later, possibly resulting in fewer mosquitoes in mid-summer in southern locations where extreme heat is predicted to coincide with decreased summer precipitation.[114]

5.4 Populations of Concern

Climate change will influence human vulnerability to vector-borne disease by influencing the seasonality and the location of exposures to pathogens and vectors. These impacts may influence future disease patterns; certain vector-borne diseases may emerge in areas where they had previously not been observed and other diseases may become less common in areas where they had previously been very common. As such, some segments of the U.S. population may be disproportionately affected by, or exposed to, vector-borne diseases in response to climate change (see also Ch. 9: Populations of Concern).

The impacts of climate change on human vulnerability to vector-borne disease may be minimized by individual- or community-level adaptive capacity, or the ability to reduce the potential exposures that may be caused by climate change. For example, socioeconomic status and domestic protective barriers, such as screens on windows and doors, can limit exposures to vector-borne pathogens.[17, 134, 135, 136, 137] From 1980 to 1999, the infected mosquito counts in Laredo, Texas, were significantly higher than in three adjoining Mexican states—yet, while there were only 64 cases of dengue fever reported in Texas, more than 62,000 dengue fever cases were reported in the Mexican states.[137] In Texas, socioeconomic factors and adaptive measures, including houses with air conditioning and intact screens, contributed to the significantly lower dengue incidence by reducing human–mosquito contact.[137] The adaptive capacity of a population may augment or limit the impacts of climate change to human vulnerability for vector-borne disease.[137]

Some segments of the U.S. population may be disproportionately affected by, or exposed to, vector-borne diseases in response to climate change.

In addition to climate factors, multiple non-climate factors also influence human exposure to vector-borne pathogens.[17, 133, 134, 135, 136, 137] Some of these include factors from an environmental or institutional context (Figure 1), such as pathogen adaptation and change, changes in vector and host population and composition, changes in pathogen infection rates, and vector control or other public health practices (pesticide applications, integrated vector management, vaccines, and other disease interventions). Other non-climate factors that influence vulnerability to vector-borne disease include those from a social and behavioral context, such as outdoor activity, occupation, landscape design, proximity to vector habitat, and personal protective behaviors (applying repellents before spending time in tick habitat, performing tick checks, and bathing after being outdoors).[138] For Lyme disease, behavioral factors, especially the number of hours spent working or playing outdoors in tick habitat as well as proximity to dense shrubbery, can increase exposure to the ticks that transmit the bacteria that causes Lyme disease.[139] For example, outdoor workers in the northeastern United States are at higher risk for contact with blacklegged ticks and, therefore, are at a greater risk for contracting Lyme disease.[140, 141, 142] If outdoor workers are working in areas where there are infected mosquitoes, occupational exposures can also occur for WNV.[143]

Individual characteristics, such as age, gender, and immune function, may also affect vulnerability by influencing susceptibility to infection.[21, 80, 140, 143, 144, 145] Lyme disease is more frequently reported in children between 5 and 9 years of age and in adults between the ages of 55 and 59,[21] and advanced age and being male contribute to a higher risk for severe WNV infections.[79, 144, 145]

Climate factors are useful benchmarks to indicate seasonal risk and broad geographic changes in disease occurrence over decades. However, human vulnerability to vector-borne disease is more holistically evaluated by examining climate factors with non-climate factors (environmental or institutional context, social and behavioral context, and individual characteristics). Ultimately, a community's capacity to adapt to both the climate and non-climate factors will affect population vulnerability to vector-borne disease.

5.5 Emerging Issues

Some vector-borne diseases may be introduced or become re-established in the United States by a variety of mechanisms. In conjunction with trade and travel, climate change may contribute by creating habitats suitable for the establishment of disease-carrying vectors or for locally sustained transmission of vector-borne pathogens. Examples of emerging vector-borne diseases in the United States include the West Nile virus introduction described above, recent outbreaks of locally acquired dengue in Florida[17, 146] and southern Texas,[147] and chikungunya cases in the Caribbean and southern Florida,[148] all of which have raised public health concern about emergence and re-emergence of these mosquito-borne diseases in the United States. Collecting data on the spread of disease-causing insect vectors and the viruses that cause dengue and chikungunya is critical to understanding and predicting the threat of emergence or reemergence of these diseases. Understanding the role of climate change in disease emergence and reemergence would also require additional research.

5.6 Research Needs

In addition to the emerging issues identified above, and based on their review of the literature, the authors highlight the following areas for potential scientific research activity on vector-borne disease. Climate and non-climate factors interact to determine the burden of vector-borne diseases on humans, but the mechanisms of these processes are still poorly understood.[149] Evidence-based models that include vector–host interaction, host immunity, pathogen evolution, and land use, as well as socioeconomic drivers of transmission, human behavior, and adaptive capacity are needed to facilitate a better understanding of the mechanisms by which climate and non-climate factors drive vector-borne disease emergence. Socioeconomic and human behavioral factors, in particular, appear to limit vector-borne diseases, even in neighboring cities.[136, 137] This is a fertile area for future research, and one that is particularly relevant for increasing our adaptive capacity to address future vector-borne disease threats.

Numerous studies have identified associations between vector-borne diseases and weather or climate, but most have focused on risk mapping or estimating associations of broad aggregates of temperature and precipitation with disease-related outcomes. A move beyond correlative associations to a more mechanistic understanding of climate's impacts on the discrete events that give rise to transmission is needed. Models must also be accompanied by empirical research to inform their parameters. Climate effects are complex, and models frequently borrow information across vector species and pathogens or make simplifying assumptions that can lead to incorrect conclusions.[150]

The risk for vector-borne diseases is highly variable geographically and over time. Monitoring responses of pathogens to climate change at a continental scale requires coordinated, systematically collected long-term surveillance datasets to document changes in vector occurrence, abundance, and infection rates. Collecting these data will provide a clearer understanding of how external drivers work in conjunction with climate change to determine the risk for human exposure to vector-borne disease.

Future assessments can benefit from research activities that:

- evaluate how climatic variables, socioeconomic factors, and human behavior influence vector-borne disease occurrence and are expected to affect human adaptive capacity and the ability to respond to future disease threats;

- enhance long-term, systematic data collection on vector and pathogen distributions to detect changes over time. Such datasets must span a range of land-use types, including urban areas, and should be coupled with data on human disease;

- utilize mechanistic models that provide an evidence-based view of climate's impacts on vector-borne diseases by explicitly accounting for the series of discrete but intertwined events that give rise to transmission. Models should be supported and validated by data specific to the disease system and include a realistic assessment of parameter uncertainty and variability;

- study the natural maintenance cycles of vector-borne pathogen evolution, emergence, and transmission as well as how climatic variables influence these cycles.

Supporting Evidence

PROCESS FOR DEVELOPING CHAPTER

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at several workshops, teleconferences, and email exchanges. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, and Federal agencies. For additional information on the overall report process, see Appendices 2 and 3.

The approach and organization of this chapter was decided after conducting a comprehensive literature review. Two case studies, Lyme disease and West Nile virus, were chosen as representative examples of vector-borne diseases in the United States for this chapter because of their high incidence rates and the body of literature available on the association between climatic and meteorological variables and occurrence of these diseases.

Regarding human outcomes related to vector-borne diseases, there is a much greater volume of published literature available on meteorological and climatic influences on vectors. As a result, our certainty in how climate change is likely to influence the vectors far exceeds our certainty in how changing climatic conditions are likely to affect when, where, and how many cases of vector-borne diseases are likely to occur.

Although the topic of zoonotic diseases was included in the original prospectus, it was later removed due to space constraints. Additionally, since both West Nile virus infection and Lyme disease are zoonotic diseases, these case studies address concepts that are common to both vector-borne and zoonotic diseases.

KEY FINDING TRACEABLE ACCOUNTS

Changing Distributions of Vectors and Vector-Borne Diseases

Key Finding 1: Climate change is expected to alter the geographic and seasonal distributions of existing vectors and vector-borne diseases *[Likely, High Confidence].*

Description of evidence base

Vector-borne diseases result from complex interactions involving vectors, reservoirs, humans, and both climate and non-climate factors. Numerous studies explain how climate variables influence the relationships between vectors, animal reservoirs, humans, and other non-climate factors to ultimately influence the spatial and temporal distribution of vector-borne disease.[11, 39, 45, 53, 101, 104, 114, 116, 123, 135]

Major uncertainties

It is certain that climate change will alter the geographic and seasonal distribution of existing vectors, pathogens, and reservoirs; the influence of climate change on the timing, prevalence, and location of specific vector-borne disease outbreaks is likely to vary depending on the influence of other significant non-climate drivers of disease occurrence.

Assessment of confidence and likelihood based on evidence

Based on the evidence that climate change will influence the temporal and spatial distributions of vectors, pathogens, and animal reservoirs, there is **high confidence** that climate change is **likely** to alter the geographic and seasonal distributions of vectors and vector-borne diseases.

Earlier Tick Activity and Northward Range Expansion

Key Finding 2: Ticks capable of carrying the bacteria that cause Lyme disease and other pathogens will show earlier seasonal activity and a generally northward expansion in response to increasing temperatures associated with climate change [*Likely, High Confidence].* Longer seasonal activity and expanding geographic range of these ticks will increase the risk of human exposure to ticks *[Likely, Medium Confidence].*

Description of evidence base

There is strong evidence that temperature affects the geographical distribution of ticks,[39, 45, 53, 67] the timing of host-seeking activity of ticks,[36, 37, 44] and even the timing of Lyme disease case occurrence.[23] However, the abundance of ticks infected with Lyme disease spirochetes, which is considered a better predictor of human risk for Lyme disease compared with nymphal density alone, has rarely been found to be strongly associated with meteorological variables.[41] Studies aimed at identifying meteorological variables associated with the geographical distribution of human Lyme disease vary in their support for demonstrating positive associations between temperature and Lyme disease.[46, 62, 63]

Major uncertainties

While the effects of temperature, precipitation, and humidity on the spatial distribution of ticks and the timing of their host-seeking activity have been clearly established in both the eastern and western regions of the United States, where Lyme disease is common, the degree to which climate change will alter Lyme disease incidence remains uncertain. The observation that meteorological variables play a lesser role than other variables in predicting the density of nymphs infected with Lyme disease bacteria raises uncertainty in how climate change will affect the distribution and magnitude of Lyme disease incidence. This uncertainty is reflected in results from models aiming to associate meteorological variables with Lyme disease incidence that yielded inconsistent findings.[46, 62, 63]

Assessment of confidence and likelihood based on evidence

Based on the evidence, there is **high confidence** that climate change, especially temperature change, is **likely** to cause shifts in the geographical distribution of ticks capable of carrying *B. burgdorferi* to more northern latitudes, the timing of host-seeking activity of ticks, and the timing of Lyme disease case occurrence. While these changes are **likely** to influence human disease, due to the few sources with limited consistency, incomplete models with methods still emerging, and some competing schools of thought, there is **medium confidence** surrounding how, and how much, climate change will influence the risk of human exposure to ticks carrying *B. burgdorferi.*

Changing Mosquito-Borne Disease Dynamics

Key Finding 3: Rising temperatures, changing precipitation patterns, and a higher frequency of some extreme weather events associated with climate change will influence the distribution, abundance, and prevalence of infection in the mosquitoes that transmit West Nile virus and other pathogens by altering habitat availability and mosquito and viral reproduction rates [*Very Likely, High Confidence].* Alterations in the distribution, abundance, and infection rate of mosquitoes will influence human exposure to bites from infected mosquitoes, which is expected to alter risk for human disease *[Very Likely, Medium Confidence].*

Description of evidence base

Higher temperatures affect the West Nile virus (WNV) system by accelerating mosquito development[102, 104] and virus reproduction rates,[101, 107, 108, 109] increasing egg-laying and biting frequency,[106] and affecting mosquito survival.[102, 126] Increased WNV activity has been associated with warm temperatures, mild winters, and drought.[101, 110, 116] Very few studies have used climate variables to predict the occurrence of human WNV cases in the United States in response to climate change (for example, Harrigan et al. 2014),[132] but available results suggest that areas of WNV transmission will expand in the northern latitudes and higher elevations driven by increasing temperature, while WNV transmission may decrease in the South if increasing temperatures reduce mosquito survival or limit availability of surface water, such as that provided by agricultural irrigation.

Major uncertainties

While the influence of temperature and precipitation on mosquito and WNV biology are fairly well-understood, these relationships vary across the United States depending on the local mosquito vector species, land use, and human activity.[112, 121] For mosquitoes in urban areas, droughts may lead to stagnation of water and increased mosquito populations that enhance WNV transmission,[110, 125] while in rural or agricultural areas, droughts may reduce mosquito populations by reducing available mosquito habitat for breeding,[101] except when irrigation compensates for drought conditions.[121] Long-term projections of human WNV risk under climate change scenarios are still in the early stages of development and are impeded by the complexities of the disease transmission cycle. Evolution of the virus, improvements in mosquito control, and the potential for long-term changes in human behavior that may affect exposure to WNV are key sources of uncertainty. For this reason, short-term, seasonal forecasts of WNV may be more fruitful in the near term and may provide information for seasonal resource allocation and public health planning.

Assessment of confidence and likelihood based on evidence

Based on the evidence, there is **high confidence** that climate change is **very likely** to influence mosquito distribution, abundance, and infection prevalence by altering habitat availability and mosquito and viral reproduction rates. While this is **very likely** to influence human disease, due to the few sources with limited consistency, incomplete models with methods still emerging, and some competing schools of thought, there is **medium confidence** surrounding how, and how much, climate change will influence human incidence of disease.

Emergence of New Vector-Borne Pathogens

Key Finding 4: Vector-borne pathogens are expected to emerge or reemerge due to the interactions of climate factors with many other drivers, such as changing land-use patterns [*Likely, High Confidence].* The impacts to human disease, however, will be limited by the adaptive capacity of human populations, such as vector control practices or personal protective measures *[Likely, High Confidence].*

Description of evidence base

The literature shows that climate change must be considered together with the many other non-climate factors of disease emergence[11, 12] and the availability of other mitigating factors, such as air conditioning, screens on windows, and vector control practices,[17, 134, 136, 137] in order to appropriately quantify the impact climate has on the risk of emerging or reemerging exotic pathogens and vectors.

Major uncertainties

It remains uncertain how climate interacts as a driver with travel-related exposures and evolutionary adaptation of invasive vectors and pathogens to affect human disease. Improved longitudinal datasets and empirical models that include vector–host interaction, host immunity, and pathogen evolution as well as socioeconomic drivers of transmission are needed to address these knowledge gaps in research on climate sensitive diseases.

Assessment of confidence and likelihood based on evidence

Based on the evidence, there is **high confidence** that a multitude of interacting factors, one of which being climate change, will **likely** influence the emergence or reemergence of vector-borne pathogens to the United States. Additionally,

there is **high confidence** that the influence of climate change on human disease is **likely** to be limited by the adaptive capacity of a population.

DOCUMENTING UNCERTAINTY

See Appendix 4: Documenting Uncertainty for more information on assessments of confidence and likelihood used in this report.

Confidence Level	
Very High	Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Likelihood	
Very Likely	≥ 9 in 10
Likely	≥ 2 in 3
As Likely As Not	≈ 1 in 2
Unlikely	≤ 1 in 3
Very Unlikely	≤ 1 in 10

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