

Effects of Climate Change on Lyme Disease Incidence: A Literature Review

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Abstract

Lyme disease is the most common vector-borne disease in the United States and Europe. This literature review will summarize and analyze the research on Lyme Disease and climate change. Lyme disease is a tick-borne disease that is spread through the bite of an infected tick. Lyme disease can be found in over 80 countries and is endemic North America, Europe, and Asia. The research included in this literature review describes and measures how climate change is affecting tick populations and therefore tick-borne diseases, specifically Lyme Disease. In recent years many studies have concluded that climate change has the potential to contribute to the geographic expansion of ticks due to an increase in temperatures. These changes in habitat range can lead to Lyme disease becoming endemic in new areas. Climate change may also affect the tick life cycle and host population distribution which can influence Lyme disease incidence. This review is relevant to public health because the identification of changes in at-risk populations for Lyme disease gives the opportunity for proper precautions to be made for those populations. A proactive approach to addressing this issue can help prepare medical care professionals, public health officials, and the public for the growing threat of Lyme disease in multiple geographic regions.

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1.0 Introduction

Lyme disease is a vector-borne disease from the bacterial genus *Borrelia* (*sensu lato*) and numerous species of tick hosts. Within the United States the bacterium *B. mayonii* can also transmit Lyme disease (Centers for Disease Control and Prevention, 2021). The bacteria *B. afzelii* and *B. garinii* also transmit Lyme disease but are only found in Europe and Asia where it is transmitted by *Ixodes ricinus* and *Ixodes persulcatus* (CDC, 2020; Marques et al, 2021). Humans become infected with bacterium in the genus *Borrelia* by the bite of an infected tick. *B. burgdorferi* will be the bacterium with the most focus throughout this review because the relevant literature about climate change and Lyme disease only focuses on North America and Europe. In North America Lyme disease is carried by two species of ticks, *Ixodes scapularis* and *Ixodes pacificus*.

Early symptoms of Lyme disease include fever, chills, headaches, and a rash referred to as Erythema migrans. Later symptoms of Lyme disease include but are not limited to facial palsy, arthritis, severe headaches, and nerve pain (CDC, 2021). Lyme disease can be treated with antibiotics after a clinical diagnosis. While treatable, some people with Lyme disease experience long term effects after treatment such as pain, fatigue, and brain fog. This condition is referred to as Post-Treatment Lyme Disease Syndrome (PTLDS). Individuals with PTLDS usually have symptoms for months but eventually see the symptoms subside (CDC, 2020). At time of publication there is not a preventative Lyme disease vaccine available.

Many recent studies have focused on the effects of climate change on Lyme disease incidence and case dispersion. Lyme disease case numbers have been increasing in various regions of the world. For example, Canada has seen more than a six-fold increase in Lyme disease cases from 144 cases in 2009 to 917 cases in 2015 (Gasmi et. al, 2017). The proliferation of studies

investigating the effects of climate change on Lyme disease emphasizes the need for this literature review.

Numerous studies and models have found that climate change is associated with the geographic expansion of ticks of the *Ixodes* genus and therefore Lyme disease cases. It is difficult to create models to predict Lyme disease incidence due to the many variables that directly and indirectly affect Lyme disease transmission (Li et al., 2019; Gray et al., 2009; Ostfeld and Brunner, 2015). The inclusion of various variables that affect Lyme disease incidence differ between models, creating different potential climate change and Lyme disease incidence scenarios. Research suggests that climate change can alter tick phenology, tick host habitat expansion, and the life cycle of ticks; all of which can contribute to changes in Lyme disease incidence.

1.1 Environment

Ticks are very sensitive to their environment and therefore have the potential to be greatly affected by climate change. This sensitivity to the temperature and humidity of the environment limits ticks to survival within certain regions and altitudes. A change in environment can potentially enable ticks to survive in a broader geographic range, and therefore Lyme disease incidence and spread would also be affected. One challenge to determine the effects of climate change on Lyme disease incidence involves the various biotic and abiotic factors that affect tick survival. Biotic factors that influence tick survival include vegetation and host density. Abiotic environmental factors that affect tick survival include temperature, humidity, soil moisture, and density of understory (Clow et. al, 2017).

1.2 Tick Life Cycle & Phenology

Ixodes scapularis ticks go through four life stages, generally over the course of two years (CDC, 2022). The four stages of life are egg, six-legged larva, eight-legged nymph, and adult. As the tick goes through these life stages it will need a new host for each stage (CDC, 2022). *Ixodes pacificus*, *Ixodes persulcatus*, and *Ixodes ricinus* also go through four life stages but it usually takes this species three years to complete its life cycle (CDC, 2022; Grigoryeva and Stanyukovich, 2016). During the questing period ticks actively search for potential by climbing up blades of grass or other plants with the goal of encountering a host that passes by. When a viable host passes the questing tick, it jumps on the host and attaches (CDC, 2020).

Hosts are also a very important part of tick survival. Ticks can have a variety of hosts such as deer, mice, squirrels, and other small mammals. However, the white-footed mouse is of great importance to ticks. A study by Bouchard et. al. (2011), found that male white-footed mice carry a higher number of nymphal and larval *I. scapularis* than other mammals such as deer, other types of mice, and squirrels. It is important to consider the potential for climate change to affect the dispersion of hosts and therefore tick populations as well. Specifically, the progression of climate change is predicted to lead to the expansion of the white-footed mouse's habitat (Dufresne et. al, 2013). As a primary host of ticks, the expansion of the white-footed mouse's habitat could lead to the geographic expansion of ticks.

1.3 Public Health Relevance

Understanding how climate change may affect Lyme disease incidence in the future can help people in areas where Lyme disease is not currently endemic prepare for changes in climate that may introduce Lyme disease in that region. A proactive approach to preventing the spread of Lyme disease is crucial to prevent an increase in Lyme disease incidence. Preparations to minimize the effects of climate change on Lyme disease incidence may include education for the public as well as those in the medical field and the development and dispersion of a preventative Lyme disease vaccine. Lyme disease is not only costly to the health of an infected individual but also healthcare systems. It is estimated that Lyme disease already costs the United States health care system between \$712 million and \$1.3 billion a year (*Lyme Disease Costs Up to \$1.3 Billion Per Year to Treat, Study Finds*, 2015). PTLDS causes individuals to repeat courses of antibiotics and continue to seek medical help, which largely contributes to the financial burden of treating Lyme disease on the United States health care system. The findings in this review will summarize where climate change will affect Lyme disease incidence and thus contribute to interventions for prioritized populations at high risk for Lyme disease.

2.0 Methodology and Methods

A literature search was conducted using key words including “Lyme Disease”, “climate change”, “effects”, “tick”, “genus *Ixodes*”, “climate zones”, “geographic expansion”, “altitudes”, “host”, “Europe”, “UK”, “North America”, “Asia”, “China”, “Mexico”. These key words were used in the literature search to include findings in all areas where Lyme disease is known to be present. Although research was reviewed for Europe, North America, Asia, and Mexico, there was only research focusing on Lyme disease and climate change within Europe and North America. Included studies must be peer-reviewed, published in the last 15 years, focus on both climate change and Lyme Disease, and published in English.

This literature search led to the inclusion of 27 publications in this literature review. All literature was found through PubMed, National Library of Medicine, and EBSCOhost. Articles within this literature review include various types of predictive models as well as studies that investigate Lyme disease incidence and tick populations over the past years. Types of models include population distribution models in conjunction with climate change models, deterministic models, and risk maps. The title and abstract of each publication were reviewed to ensure that the publication contained information regarding climate change and Lyme disease. Literature that focused on tick-borne or vector-borne disease in general but did not provide information specifically regarding both Lyme disease and climate change were not included.

3.0 Results

Of the 27 publications included in this review, 18 of the publications focused on North America, seven focused on Europe, and two focused on both North America and Europe. Eight of the included publications were models seven of those models focused on North America and one on Europe. Much of the current research surrounding the relationship between climate change and Lyme disease consist of varying prediction models as well as tick dispersion models. The predictive models largely focus on predicted climate change trends in the future and past data surrounding tick populations and Lyme disease dispersion. Some literature also utilized risk maps to analyze multiple influential factors that affect the spread of ticks and compare different climate scenarios.

3.1 North America

A publication by the Environmental Protection Agency (2019) reported that Lyme disease incidence in the United States has been steadily increasing since 1991. According to the Environmental Protection Agency (2019), the incidence of Lyme disease in 1991 was 3.74 reported cases per 100,000 people to 7.21 reported cases per 100,000 in 2018. Not only has the incidence of Lyme disease increased but the dispersion of those cases within the United States has also shifted. Figure 1 shows the change in the dispersion of Lyme disease within the United States between 1996 and 2018.

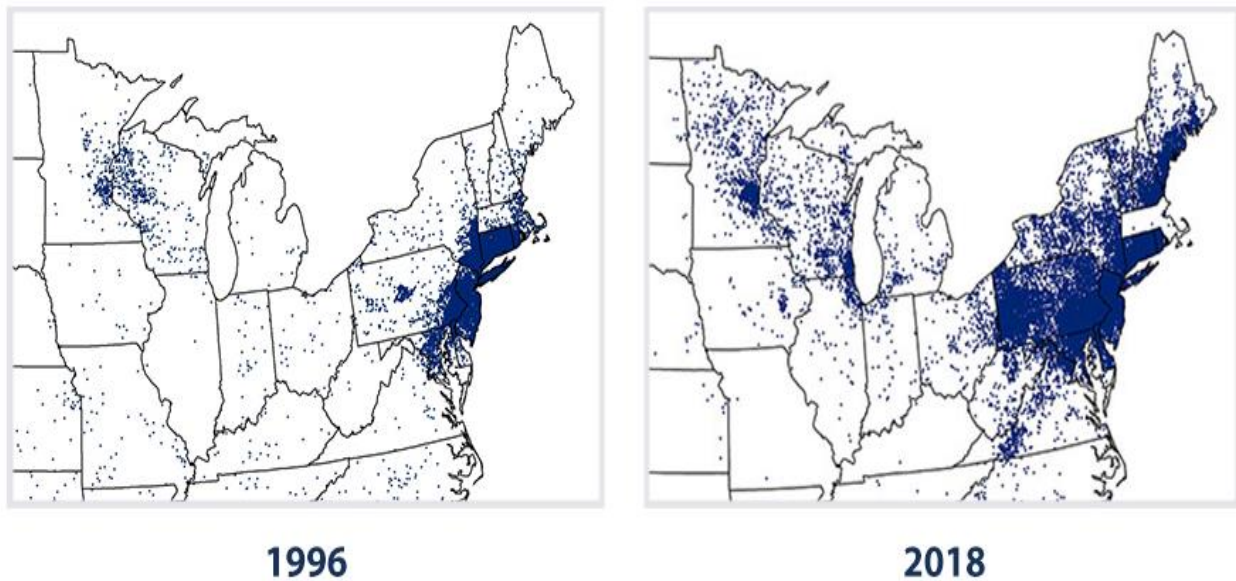


Figure 1 Dispersion of Lyme Disease cases in the United States between 1996 and 2018 (EPA, 2020)

3.1.1 Environment and Tick Habitat Expansion

While the report by the EPA highlights the importance of various factors in the dispersion of ticks and Lyme disease, such as those mentioned previously, temperature is one of the most important factors. Ticks are most active when the temperature is above 65 degrees Fahrenheit (EPA, 2019). As temperatures drop below 65 degrees, and specifically in the winter, ticks go dormant or attach to a host to survive the lower temperatures. Ticks often remain dormant in dead leaves or other layers of the forest floor when the temperature remains below 65 degrees. Shorter winters may lead to increased tick activity and therefore increased human exposure to Lyme disease (EPA, 2019). As Figure 1 clearly shows, the dispersion of Lyme disease cases within the United States has clearly expanded northward. According to the authors of this report, warming temperatures due to climate change may not only increase the areas ticks are able to survive but

may also affect tick activity. Due to tick's long life cycle, only long-term changes in climate will affect tick populations, not short-term changes in weather (Ogden & Lindsay, 2016). Long-term changes in climate that are caused by climate change and would affect tick populations include: temperature changes, precipitation changes, and humidity changes.

As temperatures have been increasing, Canada has experienced an increase in Lyme disease incidence. In 2017 there were 959 cases of Lyme disease reported in Ontario (Nelder et al., 2018). This is significantly higher than the five-year (2012-2016) average of 313 cases of Lyme disease in Ontario. Increased temperatures have led to the ability for ticks to survive in Canada, where it had previously been too cold for their survival (Bouchard et al., 2019).

Warming temperatures allow for *I. scapularis* to establish populations in regions that were previously too cold for their survival, such as Canada (Nelder et al., 2018; Ogden & Gachon 2019). Climate change has increased temperatures on a global scale; however, Canada has seen an increased rate of temperature increases compared to the rest of the globe. The mean temperature in Canada has increased by 0.75-1.2 degrees Celsius per decade over the course of the last three decades while the global mean is 0.18 degrees Celsius per decade (National Centers for Environmental Information, 2022). As temperatures in Canada have been increasing so has Lyme disease incidence. In 2017, Canada had the highest Lyme disease incidence recorded number of Lyme disease cases, 959 cases, since Lyme disease became a notifiable disease in 1988 (Nelder et al., 2018). Since Lyme disease has become a reportable disease in Canada in 1988 temperatures have increased and consequently so has Lyme disease incidence (Nelder et al., 2018, Ogden & Gachon, 2019).

With climate change *I. scapularis* will be able to expand to densely populated regions of Canada. According to Ogden et al., "Lyme disease is already endemic in the northeastern United

States and these states border some of the most densely populated regions of Canada.” The habitat expansion of ticks due to climate change has great public health significance due to the spread of ticks to highly populated areas and potentially exposing this large population to Lyme disease more frequently. Models have also predicted the expansion of *I. scapularis* northward into Canada. Using a climate model, Ogden et al., (2006) projected that *I. scapularis* will continue to move north as climate change creates temperatures that permit tick survival at higher latitudes. This model projected that as climate change progresses, fewer immigrating ticks will be needed to establish permanent tick populations in new areas (Ogden et al., 2006).

Areas of the United States are also experiencing and predicted to continue experiencing changes in Lyme disease incidence. Minnesota is also expected to experience an increase in Lyme disease incidence which researchers posit is fueled by climate change (Robinson et al. 2014). This model focused mainly on temperature and landscape changes and leaves out many environmental and human behaviors that may be affected by climate change. Using past Lyme disease incidence and climate data, Robinson et. al. (2014), concluded that climate change has a large influence on Lyme disease risk and incidence.

Although Lyme disease has the highest incidence in the northeastern United States, it can also be found in Texas and Mexico, although with lower incidence rates. Since *I. scapularis* are affected by temperature, climate change has created the question of whether southern regions may become too warm for tick survival. A model analyzing *I. scapularis* distribution in the Texas-Mexico transboundary region included a variety of environmental factors such as: annual mean temperature, precipitation of wettest and driest month, maximum temperature of warmest and coldest month, and annual precipitation (Ferria-Arroyo et al., 2014). The inclusion of various environmental factors strengthens the results produced by the model. The results of this model

project that the *I. scapularis* populations in the Texas-Mexico transboundary region will not see significant changes in distribution until 2050 (Ferria-Arroyo et al., 2014). Climate change is allowing for the geographic expansion of ticks farther north but without creating inhospitable habitats for southern regions of the United States.

3.1.2 Tick Life Cycle & Phenology

In addition to the previously discussed increase in temperature creating a more suitable habitat for *I. scapularis*, increased temperature can also affect the duration of the tick's life cycle (Eisen et. al., 2016). Eisen et. al. (2016) concluded that while the general life cycle of *I. scapularis* is two years, the life cycle of ticks living in colder regions is three to four years. The longer the life cycle of a tick, the less likely the tick is to mature into the nymphal stage, which is the primary vector of *B. burgdorferi*, due to mortality rates caused by factors such as predators or starvation (Eisen et al., 2016). As temperatures decrease, the life cycle of a tick slows down. With a longer life cycle, there is more potential for a tick to die from various natural causes before reaching the nymphal stage, which is the most important stage for the transmission of *B. burgdorferi*. Nymphs are much smaller than adult ticks making them more difficult to spot and remove, which allows for a greater risk for transmission of *B. burgdorferi* and consequently Lyme disease.

Some models predict that climate change will affect the phenology of *I. scapularis* (Levi et al., 2015). A longer period between the spring when tick nymphs emerge and the summer when larvae emerge should lead to an increase in the transmission of Lyme disease. The longer period allows for nymphs that carry *B. burgdorferi* to infect reservoir hosts before the onset of larvae season, which then promotes the transmission of the bacteria to the tick larvae (Levi et al., 2015). According to Levi et al. (2015), the asynchrony between the nymph season and larvae season gives

time for tick nymphs to effectively infect hosts populations before larvae season. Larvae are then infected with *B. burgdorferi* from the hosts inoculated by the nymphs, and the transmission cycle repeats. A model produced by Levi et al projected that climate change will not lead to increased synchrony of nymph and larva activity in North America. Increased synchrony of nymphs and larvae seasons does not give sufficient time for tick nymphs to inoculate a significant portion of the host population before the occurrence of larvae season. This projection means that climate change is predicted to continue or increase the transmission of Lyme disease (Levi et al., 2015).

Studies also project that climate change will affect the host-seeking patterns of the *Ixodes* species. Both temperature and precipitation are important factors in the host-seeking-activity of blacklegged ticks (MacDonald et al., 2020). Macdonald et al. concluded that an increase in precipitation within drier regions of California could increase the suitability of the region for host-seeking activity, questing, which could in turn lead to increases in Lyme disease transmission. An increase in duration of tick questing periods leads to more human exposure to ticks and the bacteria that causes Lyme disease *B. burgdorferi*. According to MacDonald et al, areas that are hot and dry, precipitation may be an important factor in limiting the host-seeking activity of *Ixodes pacificus*. *Ixodes pacificus* needs moisture to survive, so when in dry areas, the species must often return to the leaf litter to hydrate. This behavior then limits the time the blacklegged tick spends seeking a host and limits the potential to transmit Lyme disease. As climate change progresses, it may lead to more precipitation in previously dry areas such as northern California which may lead to more tick activity (MacDonald et al., 2020).

The reproductive number of ticks is also projected to be affected by climate change. Changes in the reproductive number of ticks can lead to changes in Lyme disease risk (McPherson et al., 2017; Ogden et al., 2014). The reproductive number “describes the propensity for a parasite

or microparasite to survive and be propagated” (McPherson et al., 2017). In this model the reproductive number was used to identify conditions in which ticks could survive and grow their population (McPherson et al., 2017). Various climate scenarios projected that even under different climate change scenarios, climate change can still affect Lyme disease risk in Canada through the increase in the R_0 of *Ixodes scapularis* due to warming temperatures (McPherson et. al., 2017). An increase in R_0 of *Ixodes scapularis* can create an increase in *Ixodes scapularis* populations and therefore increase the risk of Lyme disease. This model also projected that even in the most optimistic of the 13 climate change scenarios in the model, southern Canada is projected to have an increase in Lyme disease risk as ticks expand their habitat farther north into Canada. (McPherson et al., 2017).

3.1.3 Host Dispersion

Namely, ticks are not the only important factor in the transmission of Lyme disease. Host dispersion is also crucial to the survival of ticks. Climate change can affect host dispersion which can ultimately affect Lyme disease incidence and dispersion as well (Bouchard et al., 2019). As mentioned previously, the white-footed mouse is an extremely important host for *I. scapularis* (Bouchard et al., 2011). The spread of Lyme disease can be affected by the geographic expansion of reservoir hosts of *I. scapularis*, such as the white-footed mouse. A model was created to predict the northward expansion of the white-footed mouse under climate change. The white-footed mouse thrives in mild and short winters (Roy-Dufresne et al., 2013). Modeled temperature changes in Quebec due to climate change are predicted to create milder and shorter winters by 2050. The range of the white-footed mouse is expected to increase northward into areas of Canada such as Quebec (Roy-Dufresne et al., 2013). These predictions are significant because a change in the

dispersion of the white-footed mouse will affect the range of *I. scapularis* and the bacteria *B. burgdorferi* (Roy-Dufresne et al., 2013; Simon et al., 2014). This model has also accurately predicted current distribution of the white-footed mouse in the United States, which strengthens its credibility (Roy-Dufresne et al., 2013; Myers et al., 2009). Field and modeling approaches conducted by Simon et al. (2014) also came to the same conclusions produced in the report by Roy-Dufresne et al. (2013). Simon et al.'s (2014) model also projected the northward expansion of the white-footed mouse due to climate change and therefore the expansion of blacklegged ticks as well.

Birds can carry *I. scapularis* while migrating and transport them to new regions (Ogden et al., 2008). Some birds that carry ticks north while migrating include Blue Jays, song sparrows, Swainson's thrush, and woodpeckers. While migratory birds transport ticks north, warming temperatures due to climate change are allowing ticks to establish populations in new areas. The warming temperatures due to climate change allow *I. scapularis* to establish populations in regions of Canada where it was previously too cold for ticks to survive (Ogden et al., 2008). Leighton et al. (2012) modeled the projected effects of migratory birds on the speed of habitat establishment of *I. scapularis* under climate change. The model produced by Leighton et al. (2012) projects that ticks will be able to establish populations more quickly than in the past due to warming temperatures from climate change. Both the long-distance and local transport and dispersion of *I. scapularis* were found to be important in tick habitat expansion (Leighton et al., 2012).

The beginning of Lyme disease season in the United States is different throughout the United States. However, Lyme disease season is typically April through October. Lyme disease is extremely seasonal, with most cases being reported between June through August (CDC, 2021). Meteorological-based empirical model projected that the onset week of Lyme disease will become

0.4-0.5 weeks earlier for the years 2025-2040 in the United States (Monaghan et al., 2015). This earlier onset of Lyme disease “season” was attributed to climate change, and more specifically the increase in temperatures it is expected to cause (Monaghan et al., 2015). According to Monaghan et al. (2015), the earlier onset of Lyme disease “season” could lead to an increase in Lyme disease cases due to the potential for increased contact between humans and *Ixodes scapularis*.

3.2 Europe

Lyme disease cases have been increasing in Europe. Lyme disease is not a notifiable disease in every country within Europe, so it can be challenging to find recent and accurate incidence data (Gray et al., 2009). In comparison, Lyme disease is a notifiable disease in North America. Climate change is projected to affect both abiotic and biotic factors that affect *I. Ricinus* populations (Bregnard et al., 2020). Like the effects in North America, climate change affects the potential for tick habitat expansion, tick life cycle and phenology, and host dispersions in Europe. It is challenging to consider all these factors and decipher the extent to which climate change influences them (Ostfeld and Brunner, 2015).

3.2.1 Environment & Tick Habitat Expansion

Seed production by beech trees affected nymph populations two years after, due to the suitability of beech tree leaves as a microclimate for ticks (Bregnard et al., 2020). In addition to elevation and humidity, the seed production of the beech trees had a strong positive effect on nymph populations. Masting events refer to the production of a large mass of seeds by trees,

including, beech trees (Bregnard et al., 2020). Climate change may increase the number of masting events of beech trees, which then indirectly increases nymph populations (Bregnard et al., 2020). An increase in masting events could create an increase in reservoir hosts and ticks, leading to an increase in Lyme disease risk and incidence (Bregnard et al., 2020).

There is a negative relationship between altitude and tick populations due to temperature (Gilbert, 2009). Although climate change may create temperatures at higher altitudes in which ticks may survive, it is challenging to know what extent of this habitat expansion is due solely to an increase in temperature since other important factors in Lyme disease transmission, like hosts, are also affected by climate change. If ticks can extend their range into higher altitudes due to warming temperatures caused by climate change, that does not ensure they will still have access to other necessities for survival such as proper host populations or vegetation sub climates (Gilbert, 2009; Li et al., 2019; Ostfeld and Brunner 2015).

3.2.2 Tick Life Cycle & Phenology

A longitudinal study investigating the effects of environmental factors on tick populations found that climatic factors did not significantly affect tick populations in the Netherlands (Hartemink et al., 2019). The environmental factors included in this study by Hartemink et al. (2019) are humus layer thickness, moss abundance, blackberry abundance, and blueberry abundance. However, temperature was associated with a change in the onset of tick host-seeking activity (Hartemink et al., 2019). In other words, climate was not found to influence the number of ticks each year, but it did have an effect on the behavior of ticks. More specifically, there was a positive association between humus layer and thickness, moss, and blueberry abundance with the onset of tick activity during the various stages of the tick lifecycle (Hartemink et al., 2019).

Ticks may also be able to adjust their behavior to adapt to climate change (Gilbert et al., 2014). A study found that ticks that were from colder climates were able to quest at colder temperatures than those from warmer climate (Gilbert et al., 2014). This finding is significant in demonstrating that *I. ricinus* can adapt its behavior to the changes created by climate change. The ability for *I. ricinus* to alter its behavior based on climate suggests that its populations have the potential to remain at the very least stagnant rather than decrease due to climate change, even with decreasing temperatures (Gilbert et al., 2014). As an extensive number of previously mentioned studies report, ticks are affected by temperature, particularly warming temperatures. This report by Gilbert et al. was one of the few pieces of literature to address colder temperatures as well as warming temperatures.

It is crucial to take various factors into consideration when making predictions surrounding the relationship between Lyme disease risk and climate change. Li et al. (2019) created a model that included socioeconomic scenarios to predict the effects of climate change on Lyme disease incidence. Socioeconomic scenarios, climate change scenarios, and factors such as deer and host dispersion, temperature, and forest land cover all can affect Lyme disease incidence (Li et al., 2019). The socioeconomic scenarios consist of factors like urban land development, forest coverage, timber and food demand, and flooding in Europe (Li et al., 2019). Figure 2 outlines the various factors that affect Lyme disease risk, all which Li et al. included in their model. Lyme disease incidence is projected to increase and be altered by climate change in many models, but it may not increase under every scenario of climate change due to the interactions of many factors that affect Lyme disease risk (Li et al., 2019). Li et al. report that Lyme disease incidence is not projected to increase in the “sustainable socioeconomic scenario”. The sustainable socioeconomic scenario is a scenario in which the environment is heavily protected and greenhouse gas emissions

have been reduced to nearly zero. The reduction of greenhouse gas emissions in this scenario slow down the progression of climate change (Li et al., 2019) This caveat in which Lyme disease risk does not increase provides support to the idea that initiatives to reduce climate change may also limit Lyme disease risk.

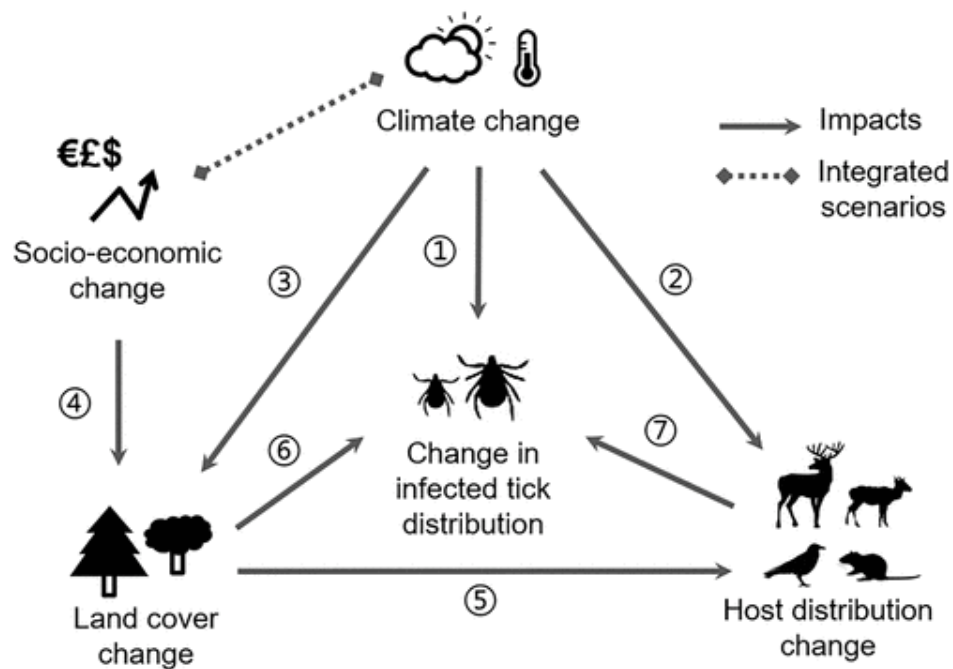


Figure 2 Key Factors that Affect Lyme Disease Risk (Li et al., 2019)

4.0 Discussion

The effects of climate change on Lyme disease incidence have major implications for public health. Since much of the current research projects that climate change will increase Lyme disease incidence and tick dispersion, it is crucial that information is utilized to prepare for those changes. Although the extent of those changes is not entirely clear, all current research in this review supports the conclusion that changes in Lyme disease incidence will occur both in North America and Europe.

The spread of Lyme disease to new areas poses a variety of challenges that must be addressed. One of these challenges is implementing effective education programs for individuals who live in areas where Lyme disease was not previously a major concern. Individuals in the newly endemic areas may not be aware of behavioral preventative strategies they can take to limit the risk of Lyme disease infection. These behavioral preventative strategies include wearing long sleeve clothing and especially long pants in wooded areas, tying hair up, and using bug repellent (CDC, 2020). It is also important to educate people on general symptoms of Lyme disease and the need to implement Lyme disease preventative measures in their daily lives. If members of a region do not see a real risk of Lyme disease, they may be less likely to implement the preventative strategies in their lives (Gould et al., 2008).

Health care professionals in regions that were not previously experiencing a high Lyme disease incidence can also benefit from the information summarized in this literature review. Public health agencies that are projected to see an increase in Lyme disease incidence in the coming years can alert health care professionals to the growing threat of Lyme disease. Reviewing common symptoms of Lyme disease may help health care professionals properly diagnose Lyme

disease in the early stages of infection. By making health care workers aware of the potentially growing threat of Lyme disease in regions, such as Canada for example, early and proper diagnoses can be made. If health care workers in a certain area are not accustomed to dealing with Lyme disease, they may not correctly diagnose the infection at the early stages which can lead to worse outcomes. As previously stated, Lyme disease costs healthcare systems billions of dollars per year and most of those resources go towards late-stage Lyme disease. By diagnosing Lyme disease in the early stages infected individuals can have better outcomes and fewer resources will be used.

There is not a preventative vaccine available for Lyme disease available at the time of publication. Changes in Lyme disease incidence due to climate change may lead to an increase in demand for a preventative vaccine. The production of the previous Lyme disease vaccine was halted due to cost and lack of interest. In 2002, a Lyme disease vaccine called LYMERix was removed from the market (Motta,2020). LYMERix was not in high demand although it was found to be safe and effective in clinical trials (Motta, 2020). A study conducted in the United States found that increased concerns regarding Lyme disease is associated with increased vaccination intentions (Motta, 2020). However, changes in Lyme disease incidence due to climate change may increase interest in a Lyme disease vaccine. Motta (2020) found that people who live in areas that are at or will be at high risk for Lyme disease, were more likely to be interested in getting a Lyme disease vaccine, if available. Two Lyme disease vaccines made by Pfizer and Valneva are undergoing clinical trials (CDC, 2021). Both vaccines would only require a single shot every year prior to the start of tick season. This is an advantage over the LYMERix vaccine which required two to three doses (Motta, 2020). Another pre-exposure prophylaxis vaccine made by MassBiologics is also expected to start human trials soon (CDC, 2021).

The information found in the studies included in this literature review can provide evidence to the public, researchers, and vaccine manufacturers that Lyme disease incidence is changing and therefore garner interest in the production and distribution of a Lyme disease vaccine. In the scenario where a vaccine is created, this literature review can give insight into what areas the vaccination efforts should be targeted. Knowing what areas are most at risk for an increase in Lyme disease incidence can assist in planning the distribution of the preventative vaccine. As the research compiled here has proven, these areas include but are not limited to Canada, the northern United States, and northern regions of Europe such as the Netherlands.

Additional research is needed to further understand the complex association between Lyme disease incidence and climate change due to the many factors that may contribute directly or indirectly. Longitudinal studies should be conducted to assess the accuracy of current models predicting changes in Lyme disease incidence due to climate change. Climate change studies are typically expensive and difficult to conduct so this poses a major challenge for researchers. Using the information from this review, further research can investigate other tick or vector borne disease that may be influenced by climate change. Specifically, areas that are seeing a rise in Lyme disease incidence due to climate change may benefit from studies observing other tick-borne diseases such as tick-borne encephalitis (TBE), Powassan Flavivirus, and Heartland bandavirus for example.

Overall, the information in this literature review gives evidence to support a proactive approach in addressing the changes in Lyme disease incidence due to climate change. The effects of climate change on tick habitat expansion, the tick life cycle and phenology and tick host dispersion have serious public health implications. Models project and evidence from past years both have concluded that North America and Europe are seeing and expected to continue to see an increase in Lyme disease incidence due to climate change. Without proactive approaches such as

those previously mentioned, we can expect to see more Lyme disease cases in areas that previously had low incidence rates.

Appendix A - Literature Summary

Author	Model Type/Methodology	Title	Publication Info	Location
Bouchard, C., Dibernardo, A., Koffi, J., Wood, H., Leighton, P., & Lindsay, L	Literature review: effect of climate and environment on tick-borne diseases	Increased risk of tick-borne diseases with climate and environmental changes	(2019) <i>Canada Communicable Disease Report</i> , 45(4), 83–89. https://doi.org/10.14745/ccdr.v45i04a02 2019	North America
Eisen, R. J., Eisen, L., Ogden, N. H., & Beard, C. B.	Literature review: how weather and climate affects Lyme disease transmission	Linkages of Weather and Climate With <i>Ixodes scapularis</i> and <i>Ixodes</i> <i>pacificus</i> (Acari: <i>Ixodidae</i>), Enzootic Transmission of <i>Borrelia burgdorferi</i> , and Lyme Disease in North America	(2015) <i>Journal of Medical Entomology</i> , 53(2), 250– 261. https://doi.org/10.1093/jme/tjv199	North America
Environmental Protection Agency	Lyme disease incidence	<i>Climate Change Indicators: Lyme Disease.</i>	(2020) Environmental Protection Agency (EPA). https://www.epa.gov/climate-indicators/climate-change-indicators-lyme-disease	North America
Feria-Arroyo, T. P., Castro- Arellano, I., Gordillo-Perez, G., Cavazos, A. L., Vargas- Sandoval, M., Grover, A., Torres, J., Medina, R. F.,	Disease risk map	Implications of climate change on the distribution of the tick vector <i>Ixodes scapularis</i> and risk for Lyme disease in the Texas- Mexico transboundary region	(2014) <i>Parasites & Vectors</i> , 7(1). https://doi.org/10.1186/1756-3305-7-199	North America

de León, A. A. P., & Esteve-Gassent, M. D.				
Leighton, P. A., Koffi, J. K., Pelcat, Y., Lindsay, L. R., & Ogden, N. H	Parametric survival regression	Predicting the speed of tick invasion: an empirical model of range expansion for the Lyme disease vector <i>Ixodes scapularis</i> in Canada.	(2012) <i>Journal of Applied Ecology</i> , 49(2), 457–464. https://doi.org/10.1111/j.1365-2664.2012.02112.x	North America
Levi, T., Keesing, F., Oggenfuss, K., & Ostfeld, R. S	16 years of field data on hosts and tick populations and a linear regression	Accelerated phenology of blacklegged ticks under climate warming	(2015) <i>Philosophical Transactions of the Royal Society B: Biological Sciences</i> , 370(1665), 20130556	North America
MacDonald, A. J., McComb, S., O'Neill, C., Padgett, K. A., & Larsen, A. E	Species distribution model and climate and land projections	Projected climate and land use change alter western blacklegged tick phenology, seasonal host-seeking suitability and human encounter risk in California	(2020) <i>Global Change Biology</i> , 26(10), 5459–5474. https://doi.org/10.1111/gcb.15269	North America

McPherson, M., García-García, A., Cuesta-Valero, F. J., Beltrami, H., Hansen-Ketchum, P., MacDougall, D., & Ogden, N. H	General circulation models from the Coupled Model Intercomparison Project Phase 5 (CMIP5)	Expansion of the Lyme Disease Vector Ixodes Scapularis in Canada Inferred from CMIP5 Climate Projections	(2017) <i>Environmental Health Perspectives</i> , 125(5), 057008. https://doi.org/10.1289/ehp57008	North America
Monaghan, A. J., Moore, S. M., Sampson, K. M., Beard, C. B., & Eisen, R. J.	Literature review: Climate change and vector-borne disease risk in UK	Effect of climate change on vector-borne disease risk in the UK.	(2015) <i>The Lancet Infectious Diseases</i> , 15(6), 721–730. https://doi.org/10.1016/s1473-3099(15)70091-5	North America
Nelder, M., Wijayasri, S., Russell, C., Johnson, K., Marchand-Austin, A., Cronin, K., Johnson, S., Badiani, T., Patel, S., & Sider, D.	Surveillance data of Lyme disease cases	The continued rise of Lyme disease in Ontario, Canada: 2017.	(2018) <i>Canada Communicable Disease Report</i> , 44(10), 231–236. https://doi.org/10.14745/ccdr.v44i10a01	North America
Ogden, N., Bigras-Poulin, M., Hanincová, K., Maarouf, A., O’Callaghan, C., & Kurtenbach, K.	Simulation model and susceptible infected carrier model	Projected effects of climate change on tick phenology and fitness of pathogens transmitted by the North American tick Ixodes scapularis	(2008) <i>Journal of Theoretical Biology</i> , 254(3), 621–632. https://doi.org/10.1016/j.jtbi.2008.06.020	North America
Ogden, N., & Gachon, P	Literature review: climate change and infectious diseases	Climate change and infectious diseases: What can we expect?	(2019) <i>Canada Communicable Disease Report</i> , 45(4), 76–80. https://doi.org/10.14745/ccdr.v45i04a01	North America

Ogden, N. H., & Lindsay, L. R.	Literature review: effect of climate change on vector-borne diseases.	Effects of Climate and Climate Change on Vectors and Vector-Borne Diseases: Ticks Are Different	(2016) <i>Trends in Parasitology</i> , 32(8), 646–656. https://doi.org/10.1016/j.pt.2016.04.015	North America & Europe
Ogden, N. H., Radojevic', M., Wu, X., Duvvuri, V. R., Leighton, P. A., & Wu, J.	Deterministic model	Estimated Effects of Projected Climate Change on the Basic Reproductive Number of the Lyme Disease Vector <i>Ixodes scapularis</i>	(2014) <i>Environmental Health Perspectives</i> , 122(6), 631–638. https://doi.org/10.1289/ehp.1307799	North America
Ogden, N. H., St-Onge, L., Barker, I. K., Brazeau, S., Bigras-Poulin, M., Charron, D. F., Francis, C. M., Heagy, A., Lindsay, R., Maarouf, A., Michel, P., Milord, F., O'Callaghan, C. J., Trudel, L., & Thompson, A	Risk maps using risk algorithm	Risk maps for range expansion of the Lyme disease vector, <i>Ixodes scapularis</i> , in Canada now and with climate change.	(2008) <i>International Journal of Health Geographics</i> , 7(1), 24. https://doi.org/10.1186/1476-072x-7-24	North America
Ogden, N., Maarouf, A., Barker, I., Bigras-Poulin, M., Lindsay, L., Morshed, M., O'Callaghan, C., Ramay, F., Waltner-	<i>Ixodes scapularis</i> population model & temperatures from 2 Global Climate models	Climate change and the potential for range expansion of the Lyme disease vector <i>Ixodes scapularis</i> in Canada.	(2006) <i>International Journal for Parasitology</i> , 36(1), 63–70. https://doi.org/10.1016/j.ijpara.2005.08.016	North America

Toews, D., & Charron, D.				
Ostfeld, R. S., & Brunner, J. L.	Literature review of climate change and <i>Ixodes</i> tick-borne diseases	Climate change and <i>Ixodes</i> tick-borne diseases of humans.	(2015) <i>Philosophical Transactions of the Royal Society B: Biological Sciences</i> , 370(1665), 20140051. https://doi.org/10.1098/rstb.2014.0051	North America & Europe
Robinson, S. J., Neitzel, D. F., Moen, R. A., Craft, M. E., Hamilton, K. E., Johnson, L. B., Mulla, D. J., Munderloh, U. G., Redig, P. T., Smith, K. E., Turner, C. L., Umber, J. K., & Pelican, K. M.	16 years of case data for spatial and temporal trends of Lyme disease and spatial regression framework	Disease Risk in a Dynamic Environment: The Spread of Tick-Borne Pathogens in Minnesota, USA	(2015) <i>EcoHealth</i> , 12(1), 152–163. https://doi.org/10.1007/s10393-014-0979-y	North America
Roy-Dufresne, E., Logan, T., Simon, J. A., Chmura, G. L., & Millien, V.	Niche model for Quebec for climatic factors, field sampling of white-footed mouse, occurrence data for white-footed mouse from the Arctos Collection Management Information System	Poleward Expansion of the White-Footed Mouse (<i>Peromyscus leucopus</i>) under Climate Change: Implications for the Spread of Lyme Disease	(2013) <i>PLoS ONE</i> , 8(11), e80724. https://doi.org/10.1371/journal.pone.0080724	North America

Simon, J. A., Marrotte, R. R., Desrosiers, N., Fiset, J., Gaitan, J., Gonzalez, A., Koffi, J. K., Lapointe, F., Leighton, P. A., Lindsay, L. R., Logan, T., Milord, F., Ogden, N. H., Rogic, A., Roy- Dufresne, E., Suter, D., Tessier, N., & Millien, V	Field data for tick habitat parameters, hierarchical partitioning analysis, logistic regression model	Climate change and habitat fragmentation drive the occurrence of <i>Borrelia</i> <i>burgdorferi</i> , the agent of Lyme disease, at the northeastern limit of its distribution.	(2014) <i>Evolutionary Applications</i> , 7(7), 750-764. https://doi.org/10.1111/eva.12165	North America
Bregnard, C., Rais, O., & Voordouw, M. J	Longitudinal study with tick collection, field-collected climate data, Climap-net data, tree masting data	Climate and tree seed production predict the abundance of the European Lyme disease vector over a 15-year period	(2020) <i>Parasites & Vectors</i> , 13(1). https://doi.org/10.1186/s13071-020-04291-z	Europe
Gilbert, L	Linear mixed models, field surveys	Altitudinal patterns of tick and host abundance: a potential role for climate change in regulating tick-borne diseases?	(2009) <i>Oecologia</i> , 162(1), 217–225. https://doi.org/10.1007/s00442-009-1430-x	Europe
Gilbert, L., Aungier, J., & Tomkins, J. L.	Laboratory experiment; Ticks exposed to different temperatures	Climate of origin affects tick (<i>Ixodes</i> <i>ricinus</i>) host- seeking behavior in response to temperature: implications for	(2014) <i>Ecology and Evolution</i> , 4(7), 1186–1198. https://doi.org/10.1002/ece3.1014	Europe

		resilience to climate change?		
Gray, J. S., Dautel, H., Estrada-Peña, A., Kahl, O., & Lindgren, E	Review of effect of climate change on tick-borne diseases	Effects of Climate Change on Ticks and Tick-Borne Diseases in Europe.	(2009) <i>Interdisciplinary Perspectives on Infectious Diseases</i> , 2009, 1–12. https://doi.org/10.1155/2009/593232	Europe
Hartemink, N., van Vliet, A., Sprong, H., Jacobs, F., Garcia-Martí, I., Zurita-Milla, R., & Takken, W	Longitudinal study	Temporal-Spatial Variation in Questing Tick Activity in the Netherlands: The Effect of Climatic and Habitat Factors	(2019) <i>Vector-Borne and Zoonotic Diseases</i> , 19(7), 494–505. https://doi.org/10.1089/vbz.2018.2369	Europe
Li, S., Gilbert, L., Vanwambeke, S. O., Yu, J., Purse, B. V., & Harrison, P. A.	Process-based models, tick distribution mapping	Lyme Disease Risks in Europe under Multiple Uncertain Drivers of Change.	(2019) <i>Environmental Health Perspectives</i> , 127(6), 067010. https://doi.org/10.1289/ehp4615	Europe
Medlock, J. M., & Leach, S. A.	Entomological review of the effect of climate change on vector-borne diseases	Effect of climate change on vector-borne disease risk in the UK.	(2015) <i>The Lancet Infectious Diseases</i> , 15(6), 721–730. https://doi.org/10.1016/s1473-3099(15)70091-5	Europe

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