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Estimating the Incidence and Economic Cost of Lyme Disease Cases in Canada in the 21st Century with Projected Climate Change

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BACKGROUND: Lyme disease (LD) is emerging in Canada owing to the range expansion of the tick vector *Ixodes scapularis* (*I. scapularis*).

OBJECTIVES: Our objective was to estimate future LD incidence in Canada, and economic costs, for the 21st century with projected climate change.

METHODS: Future regions of climatic suitability for *I. scapularis* were projected from temperature output of the North American Coordinated Regional Climate Downscaling Experiment regional climate model ensemble using greenhouse gas Representative Concentration Pathways (RCPs) 4.5 and 8.5. Once regions became climatically suitable for ticks, an algorithm derived from tick and LD case surveillance data projected subsequent increasing LD incidence. Three scenarios (optimistic, intermediate, and pessimistic) for maximum incidence at endemicity were selected based on LD surveillance, and underreporting estimates, from the United States. Health care and productivity cost estimates of LD cases were obtained from the literature.

RESULTS: Projected annual LD cases for Canada ranged from 120,000 to >500,000 by 2050. Variation in incidence was mostly due to the maximum incidence at endemicity selected, with minor contributions from variations among climate models and RCPs. Projected annual costs were substantial, ranging from CA$0.5 billion to $2.0 billion a year by 2050. There was little difference in projected incidence and economic cost between RCPs, and from 2050 to 2100, because projected climate up to 2050 is similar for RCP4.5 and RCP8.5 (mitigation of greenhouse gas emissions captured in RCP4.5 does not impact climate before the 2050s) and by 2050 the most densely populated areas of the study region are projected to be climatically suitable for ticks.

CONCLUSIONS: Future incidence and economic costs of LD in Canada are likely to be substantial, but uncertainties remain. Because densely populated areas of Canada are projected to become endemic under conservative climate change scenarios, mitigation of greenhouse gas emissions is unlikely to provide substantial health co-benefits for LD. https://doi.org/10.1289/EHP13759

Introduction

Lyme disease (LD) is the most common vector-borne disease of public health significance in the northern hemisphere.[1] The spirochetal bacteria that cause LD [*Borrelia burgdorferi sensu stricto* (*B. burgdorferi*) in North America] are transmitted among wild animal reservoir hosts (particularly rodents and birds) by hard-bodied (Ixodid) ticks: *Ixodes scapularis* in central and eastern North America and *I. pacificus* in western North America.[2] The ticks are relatively unselective regarding their hosts for blood meals, and humans acquire infection from infected host-seeking ticks encountered in woodland habitats around their homes or in woodlands that serve as workplaces or leisure and outdoor pursuit venues.[3] *I. pacificus* has been widespread in the more populated areas of British Columbia, as well as in the western US states, for many decades. For reasons associated with the ecology of *B. burgdorferi* transmission cycles maintained by this tick,[4] the incidence of LD is very low compared with the incidence in upper-midwestern and northeastern regions of North America, where *I. scapularis* is a more efficient vector.[3,5] In humans, manifestations of LD vary with different stages of progression. Early localized LD is characterized by mild illness and a spreading red rash (erythema migrans) associated with migration of spirochetes away from the bite of the infected tick and, if untreated, frequently progresses to early disseminated LD with more serious neurological or cardiac manifestations. If untreated at this stage, most patients suffer late disseminated LD with neurological and arthritis manifestations.[6] At each progression, the disease becomes more difficult to treat and has a longer impact on the patient's health.[1] A proportion of patients suffer treatment-refractory post-treatment LD syndrome (PTLDS).[7]

LD began to emerge in Canada in the last two decades owing to range expansion of the tick vector *I. scapularis* from the United States into and across southeastern and south-central parts of the country.[8] The process of invasion of this tick, and LD emergence, continues today and is well studied. This process comprises a combination of the introduction of ticks on northward migrating passerines each year,[9] climate warming allowing a greater region of Canada to be climatically suitable for *I. scapularis* populations, and establishment of reproducing populations in locations where woodland habitats provide a necessary density of host for the ticks' blood meals and appropriate duff-layer refuges from heat in the summer and freezing in the winter.[10–12] Once tick populations have become established and reach a threshold of density, transmission cycles of *B. burgdorferi* result in entomological risk of LD for the public.[10,13] These processes, and the climatic determinants, have been well validated,[8,14] and surveillance has identified that LD emergence underway in Canada is attributable to recent climate change.[5,15]

Impacts of projected future climate on LD risk in Canada have, to date, mostly focused on future projected distribution of regions of climatic suitability for *I. scapularis* populations and, by inference (and observations to date), LD risk.[12,16,17] To date

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there has been only one attempt to assess the possible future incidence according to projected climate in Canada.[18] However, this study assumed maximum possible incidence to be that of high-incidence US states[19] without correcting incidence for the substantial underreporting of LD cases ($<10\%$) in high-incidence US states, according to recent studies by the US Centers for Disease Control and Prevention (CDC).[19,20]

Here we explore the possible future incidence of LD cases in Canada. We project numbers of LD cases based on expanding climatic suitability for *I. scapularis* ticks. Expected maximum incidence, in regions where ticks have become established, was calculated using current incidence in the United States adjusted for underreporting. Given the importance of defining the magnitude of impact of diseases in dollar terms, to underpin policy and planning of prevention and control programs and program evaluation,[21] the economic cost of the projected cases was also estimated. Finally, this approach allowed comparison of LD incidence and economic costs according to different greenhouse gas concentration scenarios to explore the possible health and economic co-benefits of mitigating greenhouse gas emissions, for which there is increasing interest.[22]

Methods

Study Area

This assessment was restricted to the provinces east of the Rocky Mountains [Manitoba, Ontario, Quebec, Nova Scotia, and New Brunswick; Figure 1; constructed using ArcGIS Pro (version 3.1.0; Esri Canada)] where the majority of LD cases are currently reported. Within these provinces, the study area was restricted to municipalities located south of the boreal forest boundary. There is currently no empirical evidence that the boreal forest *a*) is a habitat supporting off-host survival of *I. scapularis* ticks to the extent that reproducing populations of the tick can become established when the climate is suitable, or *b*) supports densities of key tick hosts (white-tailed deer) and *Peromyscus* spp. mice necessary for tick population survival and *B. burgdorferi* transmission cycles. At present, it is thought that ticks found in passive tick surveillance in regions where boreal forest dominates are adventitious ticks carried in by migrating birds,[25,26] and any LD cases considered acquired in this region are likely associated with bites from adventitious ticks.[27] Similarly, to date there is no evidence of reproducing *I. scapularis* populations in woodlands of provinces west of Manitoba,[28] and *I. scapularis* found there in surveillance are also thought to be adventitious ticks, whereas LD cases acquired there are likely due to infections acquired from adventitious ticks or during unreported travel.[5,25] White-tailed deer are key reproduction hosts for *I. scapularis*, and populations of the ticks cannot persist when the deer are at low densities or absent.[29,30] White-tailed deer are absent from the islands of Newfoundland and Prince Edward Island, so reproducing populations of *I. scapularis* in these locations are unlikely even were habitat and climate suitable, and *I. scapularis* ticks collected here are again most likely to be adventitious ticks. These locations were therefore also excluded from the study region. The analysis was performed at the spatial scale of census subdivisions (CSD), according to boundaries from the 2021 Canadian census.[23]

Scenarios to Capture Uncertainty

There is considerable uncertainty in projecting the future incidence of LD in Canada that comes from three sources in our study: *a*) different possible future greenhouse gas emissions; *b*) variations among individual climate models of an ensemble used to project future climate; and *c*) uncertainty in the final LD incidence once *I. scapularis* populations and *B. burgdorferi* transmission cycles have reached their maximum equilibrium levels after they have invaded. As described in more detail in the following, these sources of uncertainty were captured by using *a*) different Representative Concentration Pathways (RCPs) that use concentrations of greenhouse gases under a scenario of significant mitigation of emissions (RCP4.5) or consistently rising concentrations of greenhouse gases under a scenario of limited mitigation of emissions (RCP8.5); *b*) the most optimistic climate model (i.e., lowest warming), most pessimistic model (i.e., highest warming) and mean of the climate model ensemble; and *c*) three different scenarios (optimistic, pessimistic, and intermediate) for final LD incidence according to incidence seen in the United States corrected for estimated underreporting in national surveillance.

Climate Suitability for Tick Establishment and LD Emergence and Climate Data Projections

The most recent European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5)[31] was used as the reference for the current climate conditions (1990–2021). North American Coordinated Regional Climate Downscaling Experiment (CORDEX)[32] program simulations were used to provide projected values for the annual cumulative degree-days above 0°C (DD $>0^\circ$C, the sum of daily average number of degrees Celsius $>0^\circ$C summed over a year) for the period 2006 to 2100 at a spatial resolution of $0.22^\circ/\sim 25$ km (WGS1984 projected coordinate system) over the study area. DD $>0^\circ$C was the metric of climate used to

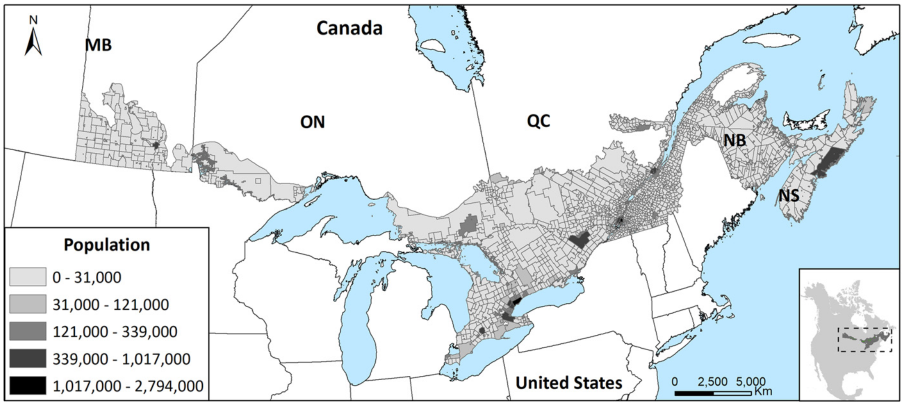

Figure 1. The population size of each census subdivision of the study area (from the Canadian Census 2021[23]) across the study area. The abbreviations MB, ON, QC, NB, and NS indicate, respectively, the provinces of Manitoba, Ontario, Quebec, New Brunswick, and Nova Scotia. An inset map of North America[24] shows the study region location.

identify climatic suitability for reproducing populations of *I. scapularis* in this and previous studies. The selection of DD >0°C is based on empirical evidence that *a*) far subzero winter air temperatures in Canada do not limit tick survival if the ticks are in woodland habitats, which usually provide duff-layer refuges for the ticks[33]; and *b*) interstadial development of ticks occurs only at temperatures >0°C (reviewed by Ogden et al.[34]) as well as field-validated modeling studies[14,35] that support the hypothesis that the limitation on *I. scapularis* population survival is the effect of temperatures >0°C across the whole life cycle that determine the duration of the tick's life cycle.[15] From these studies, minimal temperature suitability for establishment of populations of *I. scapularis* was estimated at 2,843 DD >0°C below which the life cycle is >3-y long and the tick populations cannot survive.[35] RCP4.5 and RCP8.5 were used to represent uncertainties about future greenhouse gas emissions.[36] RCP4.5 is a medium stabilization scenario leading to a stable radiative forcing level of 4.5°W/m^2 by the year 2100 (relative to the year 1750[37]). RCP8.5 is a high-emission scenario leading to a rising radiative forcing level of 8.5°W/m^2 by the year 2100.[36] The model ensemble included the following regional and global climate model combinations (three simulations per RCP)—CCCma-CanESM2-CanRCM4, CCCma-CanESM2-CRCM5-OUR, and GFDL-ESM2M-CRCM5-OUR—which were used to produce output using both RCP4.5 and RCP8.5. For each RCP, minimum, mean, and maximum DD >0°C values were extracted for each CSD for each year from the climate model simulations to represent respectively optimistic, mean, and pessimistic climate model outputs.

Prediction of the Number of Cases of LD in the Canadian Population of the Study Region

LD emergence in Canada was considered as having three phases. These are: *a*) emergence of tick populations owing to a warming climate allowing northward expansion of the geographic range of *I. scapularis*; *b*) emergence of LD risk associated with increasing tick densities and establishment of *B. burgdorferi* transmission, reflected by increasing incidence of LD cases; and *c*) endemicity when tick populations and transmission cycles are at a maximum equilibrium state and LD incidence is at a constant maximum.

Emergence of tick populations. The life cycle of *I. scapularis* in northeastern North America is multi-year, while ticks are introduced annually, being carried from more southern populations by migratory birds.[9] Therefore, the emergence of tick populations in woodland habitats in a CSD was assumed to occur by 2 y after temperature conditions in that CSD, according to climate model output, reach the 2,843 DD >0°C threshold for tick population establishment.

Emergence of LD risk. The emergence phase was assumed to begin 5 y after *I. scapularis* populations have become established (i.e., 7 y after a CSD first becomes climatically suitable for *I. scapularis*). This estimate is based on evidence of a 5-y gap between establishment of tick populations and onset of significant *B. burgdorferi* transmission in northeastern North America obtained from analysis of tick surveillance data.[13] From this time point on, it was assumed that LD incidence increases due to increases in the density of ticks where they have become established, increase in infection prevalence in questing ticks, and increase in the percentage of woodlands in a CSD where LD risk occurs.[8] We do not precisely know at what rate increase in LD risk occurs or precisely how increase in risk relates to increased incidence in LD cases. Consequently, we assumed that the increase in incidence is at least represented by the increase in incidence seen in national surveillance in recent years. Therefore, to model the emergence of LD risk, data on the number of cases reported in Canada between 1995 and 2021 (obtained from Public Health Agency of Canada surveillance[38] and from data from provincial websites prior to instigation of national surveillance in 2009[39]) were used to estimate the temporal trend in case occurrence. To current knowledge, surveillance data from 1995 to 2000 comprise small numbers of cases acquired at the only known *I. scapularis* population in Canada at that time, in a very focal location at Long Point Ontario,[40] from adventitious ticks, as well as low numbers of cases acquired on travel outside Canada. Incidence began to increase in the early 2000s (Figure S1), likely associated with emergence of *I. scapularis* populations in Canada. Some impacts of increased awareness of LD on incidence cannot be ruled out, but significant public communications effort by the Public Health Agency of Canada that occurred in 2014[41] occurred after incidence in Canada began to increase and, despite significant impact on public awareness,

Table 1. A summary of assumptions used in projecting future Lyme disease (LD) incidence and economic costs, the rationale for their use, and associated references.

Assumption	Rationale	References
Increase in LD incidence will be due to expansion of the geographic range of *I. scapularis* with little impact of any changes to the geographic range of *I. pacificus*.	No increase in incidence has been seen in British Columbia (where *I. pacificus* is the vector), and where *I. pacificus* is already widely distributed.	4,5
The boreal forest is unsuitable for *I. scapularis* populations, and possibly for *B. burgdorferi* transmission.	No evidence from surveillance or empirical studies of these occurring in boreal forests.	None
Woodlands in Saskatchewan and Alberta are unsuitable for *I. scapularis* populations.	Field surveillance data have not found evidence of reproducing *I. scapularis* populations despite evidence of regular introduction of these ticks, likely on migratory birds, in passive tick surveillance.	24,28
Populations of *I. scapularis* become established within 2 y of climate becoming suitable.	Based on knowledge of the *I. scapularis* life cycle and evidence from analysis of an 18-y-long dataset of surveillance of *I. scapularis* in Canada.	11
Cycles of *B. burgdorferi* transmission become established 5 y after populations of *I. scapularis* become established.	Based on analysis of field and passive tick surveillance data.	13
Once *B. burgdorferi* transmission becomes established in a census subdivision, LD cases increase exponentially.	Based on exponential increase in incidence in national surveillance data.	As described in the "Emergence of LD risk" and "Validation" subsections in the "Methods and Results" section.
Once fully endemic in a census subdivision, incidence will reach incidence seen in US high-incidence states.	In a few locations in Canada, incidence of reported cases is already reaching incidence seen in US high-incidence states.	45,46

did not seem to greatly change the trajectory of the increase in incidence (Figure S1). For this study, all surveillance data were used because although a small number of cases had a history of travel abroad,[5] they also could have acquired the infection in Canada. A generalized linear regression model was fitted to the log-transformed number of cases reported. The number of years since the first year of surveillance data (1995) was used as the explanatory variable in this model. The regression model produced a relationship between incidence and years since emergence (i.e., 7 y after a CSD first becomes climatically suitable of *I. scapularis*) that was then used to predict the number of cases in the future, based on the expected number of years since disease emergence in each CSD according to projected climate. All statistical analyses were performed in R (version 4.0.3; R Development Core Team). These predictions were transformed into incidence, using population estimates for 2021[30] (Figure 1) and maps of current (2020) and projected (for 2030, 2050, 2080, and 2100) incidence were constructed using ArcGIS Pro (version 3.1.0; Esri Canada).

For some CSDs that were already warmer than 2,843 DD >0°C before the start of the projected climate time-series (2006), the year of disease emergence was obtained as follows. First, the average annual temperature increase in the study area was estimated from the ERA5 reanalysis data, and this was used to back-calculate how many years previously the CSD became climatically suitable for ticks. Then the year of LD risk emergence in that CSD was estimated accounting for a period of 7 y from beginning of climatic suitability for ticks and emergence of LD risk (i.e., after 2 y for tick establishment and 5 y for *B. burgdorferi* transmission to begin). The earliest possible date of emergence in a CSD was set at 2000, which aligns with evidence from both passive and active tick surveillance data[10,11,40] and human case surveillance data (Figure S1).

To test that this algorithm did not overestimate the increase in incidence once *B. burgdorferi* transmission begins in a CSD, comparison of predicted and observed reported cases was carried out at the provincial level. For this, the number of cases predicted for each CSD by the method described above was calculated for each year for the period 2009 to 2019, without the correction factor for underreporting. Surveillance data in Canada are not available at the detail of CSD, but the Johns Hopkins Lyme and Tickborne Diseases Dashboard (https://www.hopkinslymetracker.org/) collates LD cases reported by public health departments on their websites in all Canadian provinces at the health region level.[42] Health regions in Canada now have geographic borders that are consistent with CSDs, but in most cases, there are a number of CSDs per health region.[43] Each CSD in the study area was assigned to its corresponding health region using the Intersect function in ArcGIS Pro (version 3.1.0; Esri Canada), and the predicted number of LD cases was calculated for each health region for comparison against the observed data from the Johns Hopkins Dashboard. The observed data were available for each year from 2009 to 2019, except for Manitoba and New Brunswick for which the most recent data were 2018. The comparison between the number of cases predicted by the algorithm described, by province and by year, and the number of actual cases reported in each province was performed graphically and, because numbers of cases in each year of provincial surveillance data are independent from one another (being new cases each year acquired from the environment), by calculating the mean error (ME) and root mean square error (RMSE) between predicted and observed cases at health region level in R (version 4.0.3; R Development Core Team).

Endemic state. The endemic state was assumed to occur when tick abundance and *B. burgdorferi* infection prevalence in ticks reach a maximum and stable equilibrium. To estimate LD incidence when endemicity has been reached, incidence data per 100,000 population for 2019 (i.e., prepandemic) from high-incidence US states and district (Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, Minnesota, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, Virginia, West Virginia, and Wisconsin[44]) were used to develop three different maximum thresholds at which incidence could peak in Canada. Note that West Virginia was included in this study because this state has recently been added to the first-defined 15 high-incidence states and district.[19] The three different maximum thresholds were *a*) an optimistic scenario, which used the incidence of all reported cases in the 16 high-incidence states and district; *b*) a pessimistic scenario, which used the highest reported incidence among all these states (in Vermont, which borders eastern Canada); and *c*) an intermediate scenario, which was the average of the pessimistic and optimistic two scenarios. It was assumed that, within the limits of climate warming anticipated for Canada this century, tick abundance and LD incidence per capita population would remain constant once the threshold for a region is reached and will not decline with further increases in temperature. A summary of assumptions in estimating rates of increase in incidence and maximum incidence, and rationales and evidence to support their use, is presented in Table 1.

Underreporting. The predicted incidence rates were adjusted for underreporting, to better represent the actual number of people likely to be affected by the disease each year. For this, the most recent estimate of underreporting rate of LD in North America was used, which was calculated by comparing health insurance records in the United States to cases reported to public health (CDC) during 2010–2018,[20] and from these data reported cases were multiplied by 13.7 to obtain the actual number of cases.

Economic Analysis

Based on the estimates of the number of LD cases in Canada across time, along with data extracted from the literature on *a*) the proportions of LD of each stage, *b*) the health care costs and productivity loss associated with each LD stage, and *c*) health-related quality of life [captured in disability adjusted life years (DALYs)] associated with each LD stage for the Canadian population, the economic burden of climate impacts of LD were estimated. Publicly funded health care costs (e.g., general practitioners and emergency department visits) and lost productivity due to treatment (e.g., time spent

Table 2. The proportions of Lyme disease (LD) cases expected to be of each stage of LD at the time of diagnosis and treatment, and the costs and effects associated with each LD stage.

Stages of LD	Proportion of total LD infections (%)	Cost per year (2023 Canadian dollars)	References
Undiagnosed	7.8	No health care cost, productivity cost, or DALY loss	6,47
Early localized (develop erythema migrans)	26.1	Health care cost: 110.07^a Productivity cost: $133.3 Disutility: 0.005 DALYs	6,47,48,49,50,51,52
Early localized (asymptomatic)	6	No health care cost, productivity cost, or DALY loss	6,47
Early disseminated	41.1	Health care cost: $1,040.17 Productivity cost: $4,978.08 Disutility: 0.113 DALYs	6,47,51,52,54
Late disseminated	18.9	Health care cost: $1,040.17 Productivity cost: $6,206.56 Disutility: 0.364 DALYs	6,47,51,52,54

Note: DALYs, disability adjusted life years.

[a] Assumed one physician visit per case ($84.45) and doxycycline twice per day over 3 wk ($25.62).

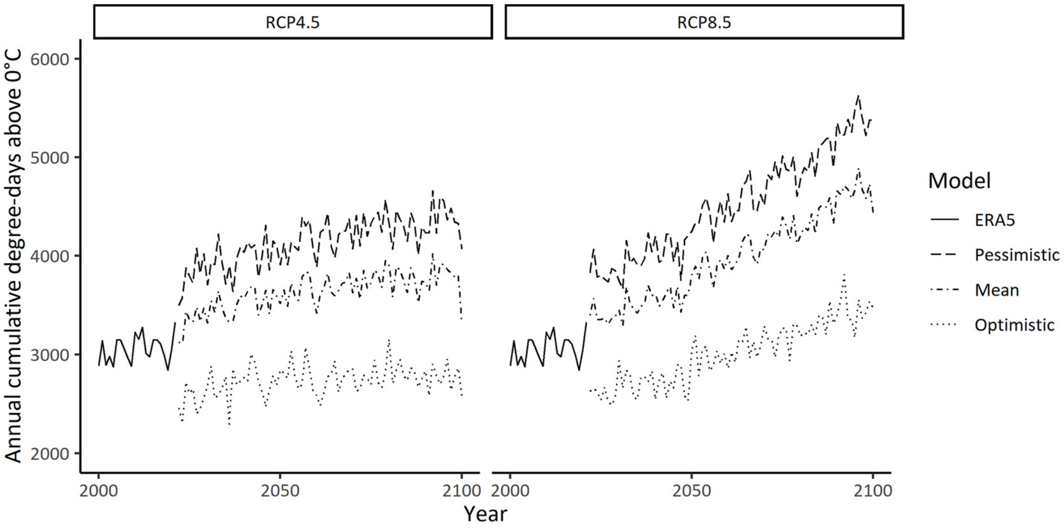

Figure 2. Average annual cumulative degree-days (DD) >0°C for the entire study area, predicted by the regional climate model ensemble for the period 2006–2100. The ERA5 reanalysis[32] was used as reference for the current climate (1990–2021) conditions. Mean, most optimistic, and most pessimistic temperature output from the model ensemble is shown for each RCP4.5 (left-hand graphs) and RCP8.5 (right-hand graphs) scenario and corresponds to projected mean DD >0°C values obtained over the whole study area. Data are presented in Excel Table S1. Note: ERA5, the most recent European Centre for Medium-Range Weather Forecasts atmospheric reanalysis; RCP, Representative Concentration Pathways.

for tick consultations) and due to illness (i.e., number of hours unable to work) were included in the analysis to capture both the impact on the health care system in Canada and the potential impact on the overall Canadian economy. The costing analysis was conducted in three steps.

In the first step, we identified the probability of LD stage (i.e., percentage of those with LD who end up at each stage) from the two most up-to-date Canadian estimates available on LD outcomes.[6,47] These two data sources captured the probability of LD by stage, which was classified into four categories: *a*) undiagnosed, *b*) early Lyme (which was further broken down into patients who developed erythema migrans and patients who were asymptomatic), *c*) early disseminated, and *d*) late disseminated.[6] The proportion of LD cases that present in each of the four categories was based on Mac et al.,[47] a study that estimated the number of cases of LD by stage in Ontario, Canada, using a microsimulation modeling approach. The proportion of asymptomatic infection at the early localized stage was based on Hatchette et al.[6] To our knowledge there are no consistent estimates of the frequency and duration of PTLDS, so costs associated with this condition were not included.

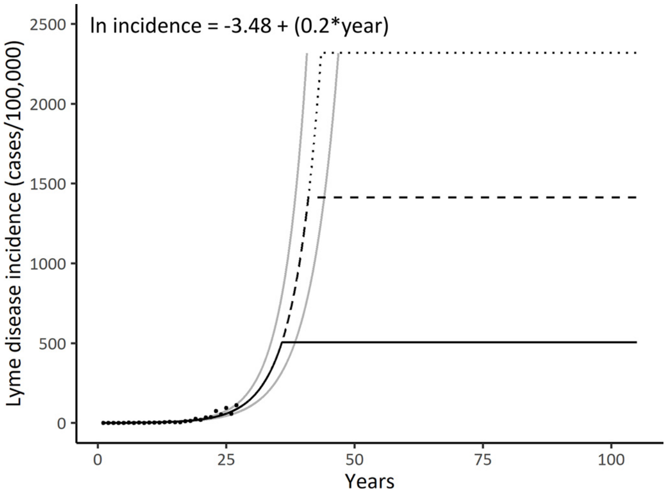

Figure 3. A graph showing the increase in Lyme disease incidence as a function of the number of years since disease emergence, obtained by a regression model using recent reported case data in Canada (shown by black dots, with the equation for the relationship is shown at the top of the graph). Gray curves are 95% confidence intervals. Three different scenarios for the maximum incidence at endemicity are shown: an optimistic scenario (solid graph), in which incidence is the current average incidence in endemic US states (505 cases/100,000; dashed graph); a pessimistic scenario (dotted graph), in which incidence is the maximum observed incidence among US states (in Vermont: 2,318 cases/100,000); and an intermediate scenario, which is the average of the optimistic and pessimistic scenarios (1,412 cases/100,000). For comparison, both observed and predicted incidence values are adjusted for estimates of underreporting seen in the US. Data are presented in Excel Table S2.

In the second step, cost and effects estimates associated with each LD stage were obtained from a rapid review of the literature as conducted by Boyd et al.[18] for their economic analysis. To ensure we accurately captured the costing estimates, and used them appropriately in our analysis, the data were extracted directly from the original sources identified by Boyd et al.[18] We included the costs associated with physician visits in Canada (from Ontario Ministry of Health and Long Term Care,[48] Canada Drugs Direct,[49] and Health Quality Ontario[50]) and the costs associated with pharmaceuticals needed for treatment. It was assumed that there was no health care cost, productivity loss, or disutility cost associated with the undiagnosed patient group and patients who were asymptomatic at the early localized stage. The health care cost associated with patients who developed erythema migrans at the early localized stage included the physician consultation fee in Ontario[48] and the cost of a course of antibiotics (doxycycline) to treat erythema migrans.[49,50] The rapid review obtained only one study[51] that

Table 3. Mean error (ME) and root mean square error (RMSE) statistics for the comparison of the predicted versus reported number of cases by health region for each province, calculated over the period from 2009 to 2019.

Province	ME	RMSE
Manitoba	−4.24	7.42
New Brunswick	−0.86	4.10
Nova Scotia	−63.40	145.08
Ontario	−10.15	32.15
Quebec	−3.84	25.40

estimated health care costs attributable to LD in Canada (in Ontario), and from this study the health care cost for patients at the early disseminated stage was obtained. Because there were no estimates for health care costs associated with late disseminated stage LD, it was assumed they would be consistent with the health care cost for patients at the early disseminated stage. Lost productivity costs for patients who developed erythema migrans at the early localized stage and for patients at the early disseminated and late persistent stages were based on van den Wijngaard et al.,[52] who used the friction cost method to estimate the cost of productivity loss due to LD, which is a conservative method for estimating the productivity impact of disease.[53] All costs were converted to 2023 Canadian dollars. The DALYs for patients who developed erythema migrans at the early localized stage and for patients at the early disseminated and late persistent stages were based on van den Wijngaard et al.[54] The LD outcome probabilities, costs, and effects values for each LD category are presented in Table 2.

In the final step of the analysis, the cost in future years (2030, 2035, 2040, 2050, 2080, and 2100) was calculated for the projected incidence across climate scenarios by applying the probabilities, costs, and effects to the number of LD cases predicted for that year and scenario according to the following equations.

$$\begin{aligned}&\mathit{Health\ care\ cost\ per\ Lyme\ disease\ case}\\&\quad=(P_{EM}\times(\mathit{Physician\ costs\ per\ case}_{EM}\\&\quad+\mathit{Pharmaceuticals\ per\ case}_{EM})\\&\quad+(P_{ED}\times \mathit{Health\ care\ costs}_{ED})\\&\quad+(P_{LD}\times \mathit{Health\ care\ costs}_{LD})\end{aligned}$$

$$\begin{aligned}&\mathit{Productivity\ loss\ per\ Lyme\ disease\ case}\\&\quad=(P_{EM}\times \mathit{Productivity\ loss}_{EM})\\&\quad+(P_{ED}\times \mathit{Productivity\ loss}_{ED})\\&\quad+(P_{LD}\times \mathit{Productivity\ loss}_{LD}),\end{aligned}$$

$$\begin{aligned}&\mathit{DALY\ per\ Lyme\ disease\ case}=(P_{EM}\times \mathit{DALY}_{EM})\\&\quad+(P_{ED}\times \mathit{DALY}_{ED})+(P_{LD}\times \mathit{DALY}_{LD})\end{aligned}$$

$$\begin{aligned}&\mathit{Total\ Lyme\ disease\ costs\ per\ year}\\&\quad=(\mathit{Number\ of\ Lyme\ disease\ cases\ per\ year}\\&\quad\times \mathit{Health\ care\ costs\ per\ Lyme\ disease\ case})\\&\quad+(\mathit{Number\ of\ Lyme\ disease\ cases\ per\ year}\\&\quad\times \mathit{Productivity\ loss\ per\ Lyme\ disease\ case}),\end{aligned}$$

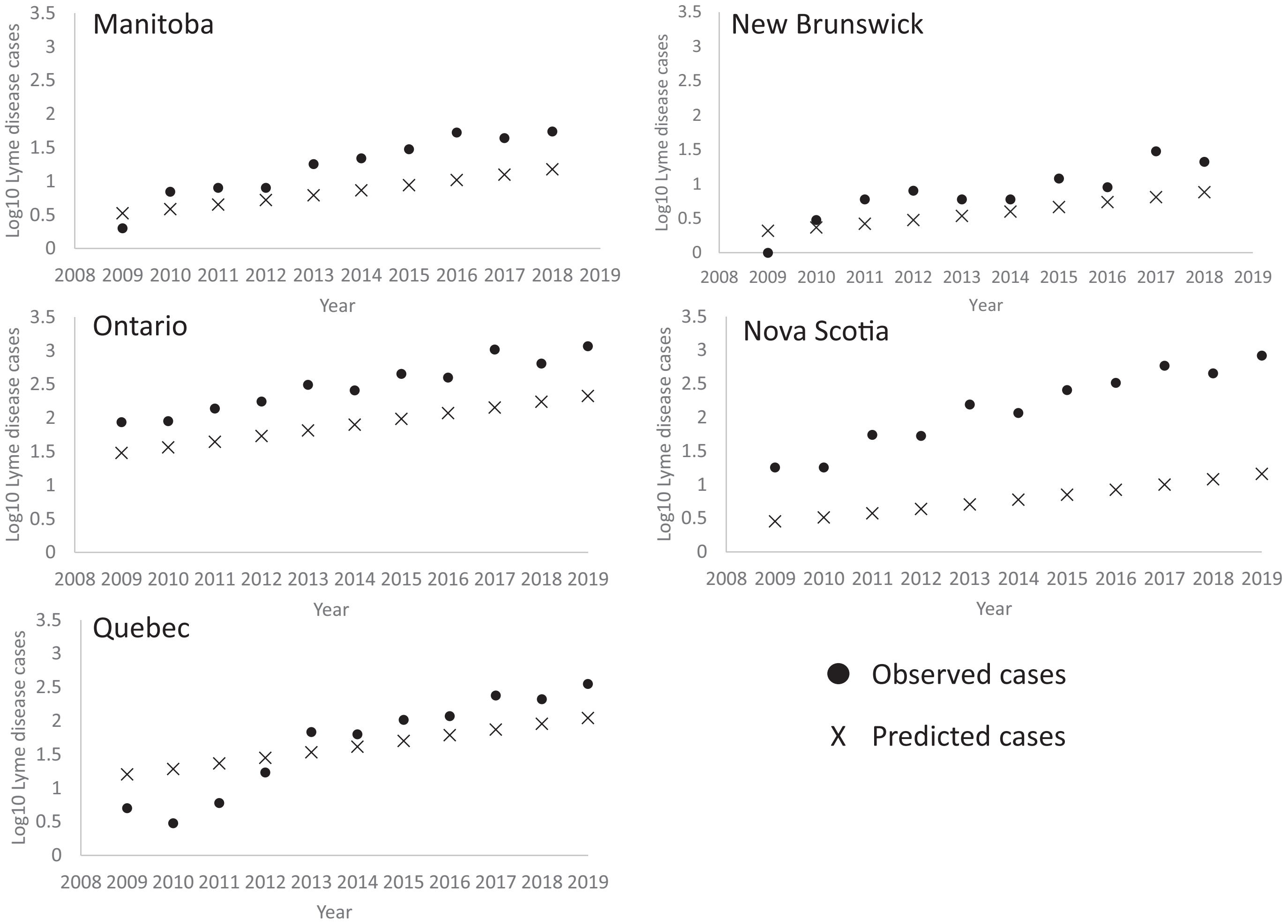

Figure 4. Graphs of the number of reported cases (expressed as the $\log_{10}$ number of cases plus 1 to account for zero values) predicted for the period 2009–2019 for each province (obtained by estimates of *a*) the year different locations became climatically suitable for *I. scapularis* ticks, *b*) a subsequent 7-y delay associated with *I. scapularis* population establishment and *B. burgdorferi* invasion, and then *c*) an increase in Lyme disease (LD) cases according to observed increases in cases in national LD surveillance as in Figure 3), and actual reported cases. Predicted cases are shown by crosses, and observed cases by filled circles. Data are presented in Excel Table S3.

Table 4. Predicted annual numbers (and incidence per 100,000 population in the study area) of Lyme disease (LD) cases in Canada in the years 2020, 2030, 2035, 2040, 2050, 2080, and 2100 under two greenhouse gas concentration scenarios (RCP4.5 and RCP8.5); optimistic, mean, and pessimistic outputs from the climate model ensemble; and optimistic, intermediate, and pessimistic thresholds for LD incidence at endemicity.

		RCP4.5						RCP8.5					
		Climate model ensemble outputs[a]						Climate model ensemble outputs[a]					
		Optimistic		Mean		Pessimistic		Optimistic		Mean		Pessimistic	
Endemicity threshold	Year	Cases (*n*)	Inc.	Cases (*n*)	Inc.	Cases (*n*)	Inc.	Cases (*n*)	Inc.	Cases (*n*)	Inc.	Cases (*n*)	Inc.
All[b]	2020	6,271	25	6,271	25	6,271	25	6,271	25	6,271	25	6,271	25
Optimistic	2030	45,545	180	45,547	180	45,552	180	45,545	180	45,550	180	45,553	180
	2035	117,977	465	117,986	465	117,998	465	117,977	465	117,991	465	117,999	465
	2040	122,389	482	122,412	483	122,443	483	122,389	482	122,426	483	122,448	483
	2050	123,418	487	123,592	487	123,816	488	123,418	487	123,695	488	123,848	488
	2080	123,658	487	128,201	505	128,296	506	123,624	487	128,239	506	128,296	506
	2100	123,702	488	128,296	506	128,296	506	124,069	489	128,296	506	128,296	506
Intermediate	2030	45,545	180	45,547	180	45,552	180	45,545	180	45,550	180	45,553	180
	2035	122,741	484	122,749	484	122,761	484	122,741	484	122,754	484	122,763	484
	2040	329,065	1,297	329,088	1,297	329,120	1,297	329,065	1,297	329,102	1,297	329,124	1,297
	2050	343,079	1,353	343,254	1,353	343,477	1,354	343,079	1,353	343,356	1,354	343,509	1,354
	2080	345,203	1,361	356,083	1,404	358,265	1,412	345,170	1,361	356,431	1,405	358,265	1,412
	2100	345,436	1,362	358,234	1,412	358,265	1,412	346,097	1,364	358,265	1,412	358,265	1,412
Pessimistic	2030	45,545	180	45,547	180	45,552	180	45,545	180	45,550	180	45,553	180
	2035	122,741	484	122,749	484	122,761	484	122,741	484	122,754	484	122,763	484
	2040	330,780	1,304	330,804	1,304	330,835	1,304	330,780	1,304	330,818	1,304	330,839	1,304
	2050	561,949	2,215	562,123	2,216	562,347	2,217	561,949	2,215	562,226	2,216	562,379	2,217
	2080	566,749	2,234	583,477	2,300	588,234	2,319	566,716	2,234	584,101	2,303	588,234	2,319
	2100	567,170	2,236	588,133	2,319	588,234	2,319	567,951	2,239	588,234	2,319	588,234	2,319

Note: ERA5, the most recent European Centre for Medium-Range Weather Forecasts atmospheric reanalysis; inc, incidence in the study area; RCP, Representative Concentration Pathways.

[a] Minimum, mean, and maximum values obtained from the climate model ensemble to represent the optimistic, mean, and pessimistic scenarios.

[b] The estimates for 2020 are based on climatic conditions obtained from the ERA5 reanalysis, and the different endemicity thresholds have no impact on them. Cases and incidence for 2020 is adjusted for levels of underreporting seen in the US.

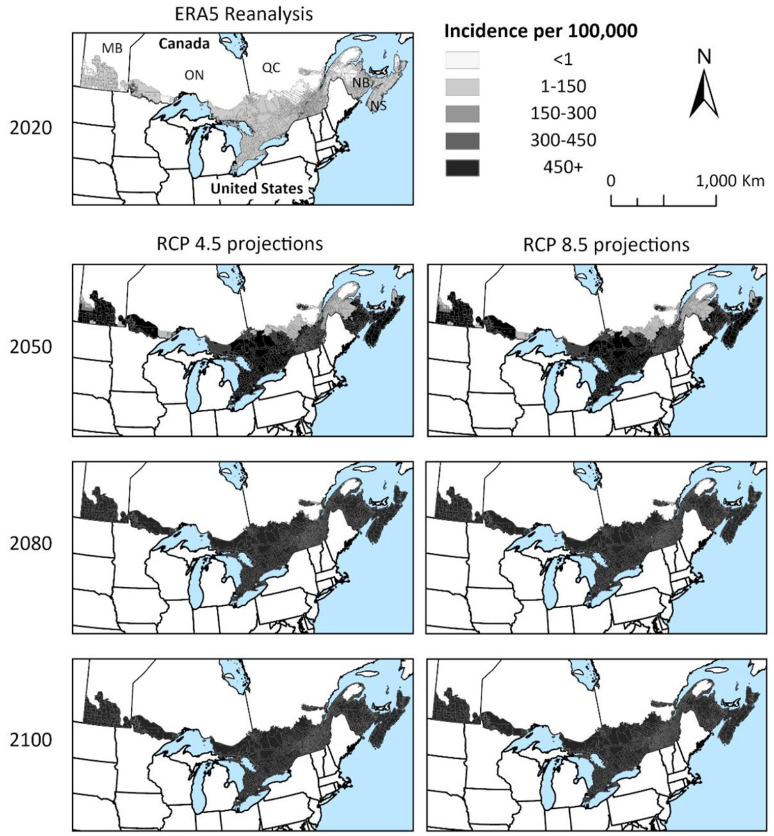

Figure 5. Maps showing projected Lyme disease (LD) incidence in each census subdivision in selected years according to the mean of the climate model ensemble under different greenhouse gas concentration scenarios (RCP4.5 and RCP8.5). For simplicity only maps obtained using the optimistic threshold for LD incidence at endemicity are shown. LD is considered as emerging once climatic suitability for ticks (DD >0°C >2,843) is achieved for 2 consecutive years and after a 5-y delay for *B. burgdorferi* invasion. Future incidence is predicted based on an exponential increase in the number of cases once the disease emerges, with the maximum incidence set to the average observed in high-incidence US states (i.e., the optimistic maximum incidence at endemicity) and corrected for underreporting. The abbreviations MB, ON, QC, NB, and NS indicate, respectively, the provinces of Manitoba, Ontario, Quebec, New Brunswick, and Nova Scotia. Data are presented in Excel Table S4. Note: ERA5, the most recent European Centre for Medium-Range Weather Forecasts atmospheric reanalysis; RCP, Representative Concentration Pathways.

$$\begin{aligned}&\mathit{Total\ Lyme\ disease\ DALY\ loss\ per\ year}\\&\quad=(\mathit{Number\ of\ Lyme\ disease\ cases\ per\ year}\\&\quad\times\mathit{DALY\ loss\ per\ Lyme\ disease\ case}),\end{aligned}$$

where EM is erythema migrans, ED is early disseminated, and LD is late disseminated.

Because the costs were captured for only 1 y, we did not capture longer-term costs and consequences associated with LD. We assumed the proportions of cases in different stages would remain constant and that costs were stable across all years (i.e., did not account for potential inflation). All costs were inflated to, and presented in, 2023 Canadian dollars, and DALYs are presented as total number of years lost due to LD. We measured only undiscounted costs given that costs and effects of treatments were considered contemporaneous and did not have different values based on when they occurred.[51]

Results

In most cases, data for figures are presented in a Supplemental Excel file. However, when the data are publicly available, their sources are identified.

Climate

Projected DD >0°C according to the different RCPs (with output from the mean, most pessimistic, and most optimistic climate models of the ensemble) are shown in Figure 2. For simplicity, DD >0°C for the whole study area is shown. DD >0°C is projected to more than double by the end of the 21st century according to the RCP8.5/pessimistic model scenario compared with the current climate conditions.

Prediction of the Number of Cases of LD in the Canadian Population of the Study Region

The equation obtained from a regression model of national surveillance data, which was used to estimate reported cases after the emergence of LD transmission cycles in a CSD was natural logarithm (ln) incidence $= -3.48 + (0.2 \times \text{year})$, where year is the number of years since emergence, and incidence is per 100,000 population. The increase in incidence through the emergence phase to the endemic phase based on this relationship (with three scenarios for the maximum incidence at endemicity) is shown in Figure 3. The combined approach of *B. burgdorferi* transmission beginning (and LD cases beginning to be acquired) 7 y after climatic suitability begins in each CSD, followed by increasing incidence according to that seen in national surveillance, underestimated observed increases in incidence in each province as evident graphically and by negative ME values for each province (Table 3, Figure 4). Observed and predicted incidence were most similar for the provinces of Manitoba, Quebec, and New Brunswick, but underestimation of observed cases was marked for Ontario and Nova Scotia, as shown graphically and by high RMSE values for these provinces (Table 3, Figure 4).

Projected Numbers of Cases of LD in the Canadian Population of the Study Region with Climate Change

The projected numbers of LD cases according to the different RCPs, climate model outputs, and scenarios for the maximum incidence at endemicity are presented in Table 4, and the spatial evolution of incidence by CSDs is shown in Figure 5. These range from 33,000 cases a year by 2030 to between 100,000 and 500,000 cases a year by 2100. The factor that caused the greatest variation among scenarios was the threshold for incidence of LD at full endemicity. Projections suggest much of the population in the study area is at risk of LD by 2050, and almost all by 2080, with little difference in progression between the greenhouse gas concentrations scenarios of RCP4.5 and RCP8.5. It was estimated that nearly 67% of the Canadian population of the study region will be living in a CSD endemic for LD by 2050. A comparison of climate model and ERA5 reanalysis DD >0°C values for the CSDs of the study area, for the 2006–2021 period that these data overlap, is presented in Excel Table S5.

Table 5. Undiscounted predicted annual cost of Lyme disease (LD) cases in Canada in Canadian dollars (millions) in the years 2020, 2030, 2035, 2040, 2050, 2080, and 2100 under two greenhouse gas concentration scenarios (RCP4.5 and RCP8.5); optimistic, mean, and pessimistic outputs from the climate model ensemble; and optimistic, intermediate, and pessimistic thresholds for LD incidence at endemicity.

		RCP4.5						RCP8.5					
		Climate model ensemble outputs[a]						Climate model ensemble outputs[a]					
		Optimistic		Mean		Pessimistic		Optimistic		Mean		Pessimistic	
Endemicity threshold	Year	HC	Prod	HC	Prod	HC	Prod	HC	Prod	HC	Prod	HC	Prod
All	2020	3.64	18.14	3.64	18.14	3.64	18.14	3.64	18.14	3.64	18.14	3.64	18.14
Optimistic	2030	29.73	148.19	29.73	148.20	29.74	148.22	29.73	148.19	29.74	148.21	29.74	148.22
	2035	77.02	383.88	77.02	383.91	77.03	383.94	77.02	383.88	77.03	383.92	77.03	383.95
	2040	79.90	398.23	79.91	398.31	79.93	398.41	79.90	398.23	79.92	398.35	79.94	398.42
	2050	80.57	401.58	80.68	402.15	80.83	402.87	80.57	401.58	80.75	402.48	80.85	402.98
	2080	80.73	402.36	83.69	417.14	83.76	417.45	80.71	402.25	83.72	417.27	83.76	417.45
	2100	80.76	402.50	83.76	417.45	83.76	417.45	81.00	403.70	83.76	417.45	83.76	417.45
Intermediate	2030	29.73	148.19	29.73	148.20	29.74	148.22	29.73	148.19	29.74	148.21	29.74	148.22
	2035	80.13	399.38	80.13	399.40	80.14	399.44	80.13	399.38	80.14	399.42	80.14	399.45
	2040	214.82	1,070.72	214.84	1,070.80	214.86	1,070.90	214.82	1,070.72	214.85	1,070.84	214.86	1,070.91
	2050	223.97	1,116.32	224.09	1,116.89	224.23	1,117.61	223.97	1,116.32	224.15	1,117.22	224.25	1,117.72
	2080	225.36	1,123.23	232.46	1,158.63	233.89	1,165.73	225.34	1,123.12	232.69	1,159.76	233.89	1,165.73
	2100	225.51	1,123.99	233.87	1,165.63	233.89	1,165.73	225.94	1,126.14	233.89	1,165.73	233.89	1,165.73
Pessimistic	2030	29.73	148.19	29.74	148.22	29.74	148.22	29.73	148.19	29.74	148.21	29.74	148.22
	2035	80.13	399.38	80.14	399.44	80.14	399.44	80.13	399.38	80.14	399.42	80.14	399.45
	2040	215.94	1,076.30	215.98	1,076.48	215.98	1,076.48	215.94	1,076.30	215.97	1,076.42	215.98	1,076.49
	2050	366.86	1,828.48	367.12	1,829.78	367.12	1,829.78	366.86	1,828.48	367.04	1,829.38	367.14	1,829.88
	2080	369.99	1,844.10	384.02	1,914.01	384.02	1,914.01	369.97	1,843.99	381.32	1,900.56	384.02	1,914.01
	2100	370.27	1,845.47	384.02	1,914.01	384.02	1,914.01	370.78	1,848.01	384.02	1,914.01	384.02	1,914.01

Note: HC, health care costs; prod, productivity costs; RCP, Representative Concentration Pathways.

[a] Minimum, mean, and maximum values obtained from the climate model ensemble to represent the optimistic, mean, and pessimistic scenarios.

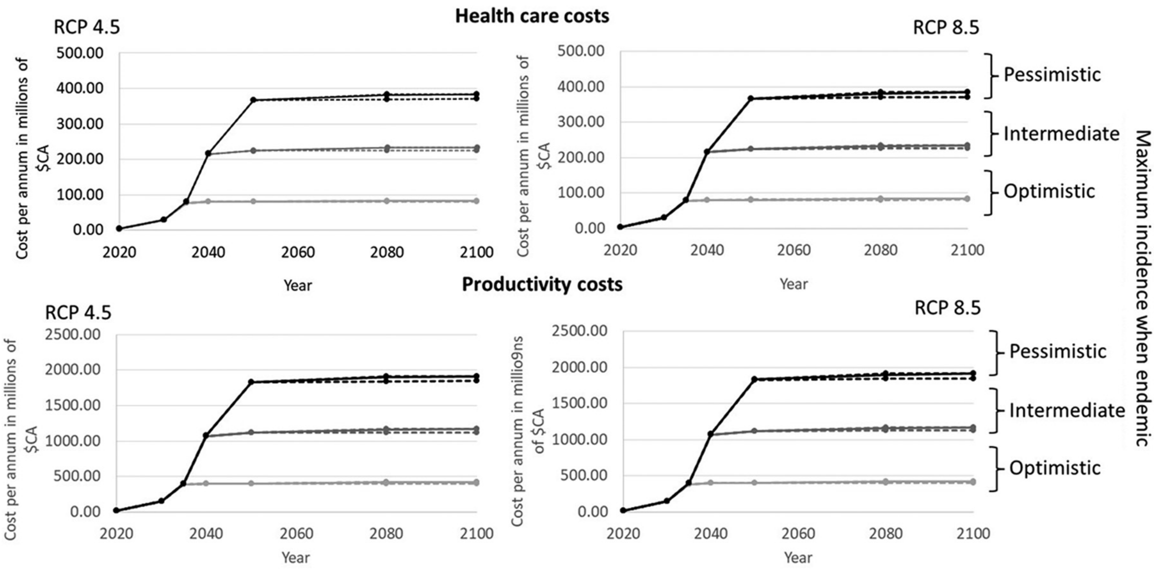

Figure 6. The estimated annual health care and productivity costs (upper graphs) and total annual costs (lower graph) under different greenhouse gas concentration scenarios (RCP4.5 and RCP8.5, but for simplicity for total costs only graphs for RCP4.5 are shown), and scenarios for optimistic, intermediate, and pessimistic maximum incidence when Lyme disease becomes endemic in census subdivisions (respectively light gray, dark gray, and black graphs). Solid line graphs are the estimates obtained from projected incidence using the mean of the climate model ensemble, and dotted line graphs below and above the solid lines are, respectively, estimates obtained from projected incidence using the most optimistic and the most pessimistic climate models. For the graph of total costs, the graphs for the mean of the climate model ensemble obscures graphs for the most optimistic and the most pessimistic climate models. Data are presented in Excel Table S6. Note: RCP, Representative Concentration Pathways.

Economic Analysis

Results of economic analysis are shown in Table 5 and Figure 6 (for health care and productivity costs), and estimated DALYs are shown in Figure 7. By 2100 the estimated annual costs ranged from $0.5 billion to $2.3 billion depending on the level of incidence reached at endemicity and, as for the LD cases, the costs rose from low levels to high levels by 2050 and plateaued thereafter. DALYs reached values of 10,000 to 60,000, depending on the level of incidence reached at endemicity, following the same temporal pattern as costs. Compared with the effect of level of incidence at endemicity, variations among climate models and RCPs were very minor for both costs and DALYs. The main costs came from disseminated LD cases, followed by late persistent LD, and, in both cases, productivity losses accounted for the majority of the costs (Figure 8). For DALYs, late persistent LD patients contributed the most to burden, followed by disseminated LD cases (Figure 8). Early localized cases of LD contributed very little to health or economic burden.

Discussion

In this study, the projected annual numbers of LD cases in Canada ranged between 120,000 and >500,000 by 2050 depending on scenario. Subsequently, incidence was projected to increase more slowly through 2100. This pattern is due to the majority of Canada from Manitoba east, and south of areas with boreal forest, being projected to become climatically suitable for *I. scapularis* by 2050. Three types of scenario were explored, including *a*) scenarios for different levels of greenhouse gas concentrations (the RCPs), *b*) a climate model ensemble output (most optimistic model, most pessimistic model, and mean of the models), and *c*) three scenarios for the maximum incidence when LD risk becomes endemic in a CSD. Of these, the last was the source of the greatest variations in projected incidence, with differences among climate models having a comparatively negligible effect. There was also little difference between RCPs in the projected incidence. This is because climate projections up to 2050 are very similar for RCP4.5 and RCP8.5 because mitigation of greenhouse gas emissions represented in

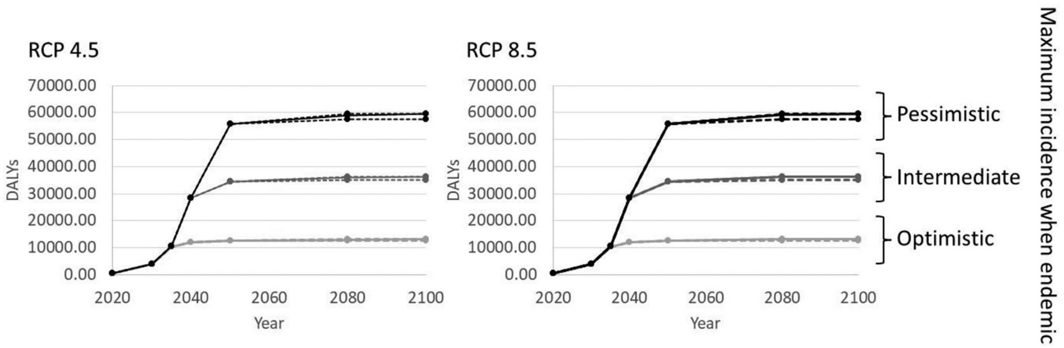

Figure 7. The estimated annual disability adjusted life years (DALYs) under different greenhouse gas concentration scenarios (RCP4.5 and RCP8.5), and optimistic, intermediate, and pessimistic maximum incidence when Lyme disease becomes endemic in census subdivisions (respectively light gray, dark gray, and black graphs). Solid line graphs are the estimates obtained from projected incidence using the mean of the climate model ensemble, and dotted line graphs below and above the solid lines are, respectively, estimates obtained from projected incidence using the most optimistic and the most pessimistic climate models. Data are presented in Excel Table S6. Note: RCP, Representative Concentration Pathways.

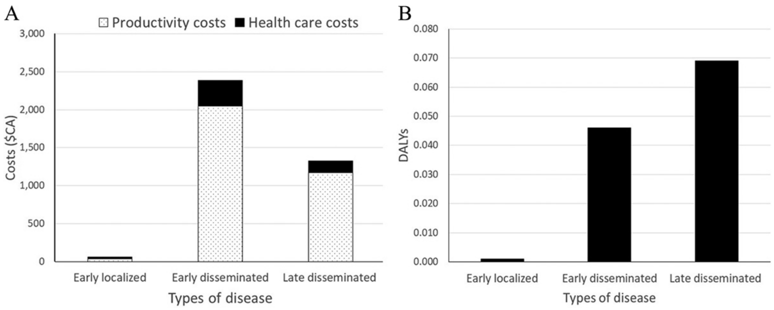

Figure 8. Bar graphs showing (A) disability adjusted life years (DALYs) and (B) the relative source of costs per person infected with Lyme disease. Data are presented in Excel Table S7.

RCP4.5 do not impact climate until after the 2050s,[36] by which time most of the subboreal regions of Canada under study are already projected to be climatically suitable for the ticks. Expansion of climatic suitability from 2050 to 2080 occurred in some regions of Canada, particularly in northern New Brunswick, eastern and central Quebec, and locations in northwestern Ontario and southern Manitoba (Figure 4). However, these regions have low population density (Figure 1), so the emergence of LD endemicity there does not result in large increases in incidence. In Canada, LD incidence is increasing at an approximately exponential rate, with some interannual variation in increases.[38] The increase is associated with transmission by *I. scapularis* ticks (from Manitoba eastwards), without evidence of increases in British Columbia where the vector of LD is *I. pacificus*, which already has a wide geographic distribution in this province.[5] We do not know which of the scenarios for incidence at endemicity will be realised in Canada. However, the algorithm used to estimate the rate of increase in incidence during the LD emergence phase underestimated the increase in many provinces when compared against observed incidence, so all of the scenarios appear to be possible at present and the algorithm is not overestimating cases and appears to be conservative. The causes of variations among provinces, in the degree to which estimates of incidence from the algorithm underestimated observations, require further study to better understand and project how increased geographic range of *I. scapularis* and *B. burgdorferi* transmission cycles result in changes in LD incidence. To our knowledge, to date only surveillance data from Canada have straddled the period when emergence of LD has begun. We did not include limitations on incidence associated with high temperatures as Boyd et al. did,[18] because empirical data from the United States, showing continued increases in tick populations and LD incidence in southern parts of high-incidence states, does not support this idea.[55]

The projected annual societal cost of LD cases was substantial, ranging from $0.5 billion to $2.3 billion a year by 2100, with, as for incidence, little difference between 2050 and 2100, and a large range due to variations among scenarios for the peak incidence at endemicity. Approximately 80% of the costs came from societal productivity costs and 20% from health care costs. Both health care and productivity costs for early LD cases were proportionally very small compared with the costs for disseminated LD cases, with nearly all the estimated productivity costs being associated with disseminated LDs cases. Estimations of the economic costs of cases of LD is an ongoing research endeavor in general, and in Canada in particular, and estimates of the economic cost of LD with climate change will likely have to be revisited in the future. Projected DALYs due to LD ranged from 12,000 to 70,000 a year by 2100, but these are not given dollar values given that, in general, costing of DALYs is associated with mortality, which was not considered here. The projected incidence of LD cases, and economic costs, estimated here were approximately two orders of magnitude greater than those estimated by Boyd et al.,[18] which is unsurprising considering they did not account for a >10-fold underreporting of cases. Another difference was that Boyd et al.[18] assumed that incidence of LD is reduced in particularly warm climates (where mean annual temperature is >15°C) based on the nonlinear relationship between incidence and mean annual temperature identified in US surveillance data by Dumic and Severnini,[56] who inferred from this relationship that higher temperatures inhibit transmission possibly by effects on tick survival. However, this assumption is likely flawed at the range of temperatures currently experienced in the United States. Low incidence in warmer parts of high-incidence states reflects recent low densities of human-biting northern clade *I. scapularis* ticks in the southern parts of the high-incidence states,[57] but that is changing. The northern clade ticks are expanding their range southward as well as northward. Southward range expansion is associated with continued spread of ticks from historical refugial zones in the northeastern and upper-midwestern United States simply to more completely fill their ecological niche in the region and is unlikely to be a process related to climate change.[55]

Key uncertainties in our estimates included uncertainty about the incidence of LD at endemicity (including uncertainty as to the degree that underreporting estimates in the United States can directly apply to Canada), uncertainties around how LD entomological hazard will spread in Canada in different habitats and human populations and result in LD cases and whether or not the boreal forest will actually act as a barrier to geographic spread of *I. scapularis* ticks and *B. burgdorferi*. Data on LD cases in Canada prior to the start of national surveillance in 2009 were obtained from individual provinces in which LD was notifiable before 2009, but not necessarily with similar case definitions, so there remain uncertainties regarding these data. We have not included consideration of loss of woodland needed for LD risk to occur (as included in some comparable studies in Europe[58]) that might be considerable for some socioeconomic pathways leading to RCP8.5[59] and somewhat limit incidence at endemicity and rates of tick spread under this scenario. Impacts of temperature on *I. scapularis* populations as explored here assume, on the basis of field experiments, that woodland habitats provide refugia for ticks from direct tick-killing effects of extreme cold, heat, and drought, but it is possible that increasingly extreme weather with climate change will exceed the capacity of refugia to protect the ticks in a way that is not currently possible to predict.[16] We did not consider that the population of Canada is anticipated to grow,[60] and this could have impact on projected incidence directly, or indirectly, because increasing housing impacts landcover with habitat suitable for ticks.

Nevertheless, our intermediate estimate of the projected cost of LD cases is in the order of CA$1 billion a year, and that cost is projected to be reached within the next two decades. This is a substantial economic burden, with the range estimate being 2–10 times the annual estimated cost of pertussis in Canada.[61] Estimates of incidence from the United States, accounting for underreporting, are those obtained with the implementation of efforts to prevent LD. Recent studies identified the high economic impact of a vaccine for COVID-19 when compared with counterfactual scenarios,[62] which underlines the potential importance of the development of an effective vaccine against LD. It also underlines, in the absence of a vaccine, the importance of efforts to prevent early LD cases (by, e.g., increasing public and physician awareness) becoming disseminated cases, for which the personal costs to the well-being of patients, and the economic costs are much greater. In this study, economic costs of LD are considered as a consequence of spread of the geographic range of *I. scapularis*. However, this tick also transmits other zoonotic pathogens, including *Anaplasma phagocytophilum*, *Babesia microti*, *Borrelia mayonii*, *Borrelia miyamotoi*, and deer tick virus, which are emerging in Canada,[63] and the economic costs of illnesses caused by these pathogens, and PTLDS, would be in addition to those estimated in this study.

It is important to consider the health co-benefits of mitigation of greenhouse gas emissions (RCPs and their influences on climate changes), and clearly there were fewer LD cases, and lower economic costs, with the RCP4.5 model compared with the RCP8.5. However, the difference was small, owing to the climate warming under RCP4.5 being sufficient to allow emergence of LD risk in the most densely populated parts of central and eastern Canada. Further studies are needed to explore the impact of mitigation on the risk of LD for the population residing within the boreal forest regions. If the boreal forest is in fact suitable for ticks and their hosts once climatic suitability is reached, then the population there, albeit small ($\sim 1.7\%$ of the population of Manitoba, Ontario, and Quebec combined live in the regions of these provinces excluded from the study region[23]) may well be protected from LD risk by mitigation of greenhouse gas emissions.

In conclusion, we project a significant health and economic burden associated with the emergence of LD in Canada driven by climate change. This adds to the many ways climate change will impact the economy, resulting also from compound effects from both environmental, health, and other vulnerability and exposure factors. However, as noted in the last US Global Change Research Program report,[64] socioeconomic drivers, along with altered human behaviors and ecosystems, and increased adaptive capacity in the face of climate change,[65] as well as changes in the environmental hazard, determine exposures and transmission of vector-borne diseases.

Acknowledgments

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All data are available in the Supplemental Excel file, or via open access links identified in the references.

References

1. Lantos PM, Rumbaugh J, Bockenstedt LK, Falck-Ytter YT, Aguero-Rosenfeld ME, Auwaerter PG, et al. 2021. Clinical practice guidelines by the Infectious Diseases Society of America (IDSA), American Academy of Neurology (AAN), and American College of Rheumatology (ACR): 2020 guidelines for the prevention, diagnosis and treatment of Lyme disease. Clin Infect Dis 72(1):1–8, PMID: 33483734, https://doi.org/10.1093/cid/ciaa1215.
2. Foster E, Maes SA, Holcomb KM, Eisen RJ. 2023. Prevalence of five human pathogens in host-seeking *Ixodes scapularis* and *Ixodes pacificus* by region, state, and county in the contiguous United States generated through national tick surveillance. Ticks Tick Borne Dis 14(6):102250, PMID: 37703795, https://doi.org/10.1016/j.ttbdis.2023.102250.
3. Mead P. 2022. Epidemiology of Lyme disease. Infect Dis Clin North Am 36(3):495–521, PMID: 36116831, https://doi.org/10.1016/j.idc.2022.03.004.
4. Morshed MG, Lee MK, Man S, Fernando K, Wong Q, Hojgaard A, et al. 2015. Surveillance for *Borrelia burgdorferi* in *Ixodes* ticks and small rodents in British Columbia. Vector Borne Zoonotic Dis 15(11):701–705, PMID: 26502354, https://doi.org/10.1089/vbz.2015.1854.
5. Gasmi S, Ogden NH, Lindsay LR, Burns S, Fleming S, Badcock J, et al. 2017. Surveillance for Lyme disease in Canada: 2009–2015. Can Commun Dis Rep 43(10):194–199, PMID: 29770045, https://doi.org/10.14745/ccdr.v43i10a01.
6. Hatchette TF, Davis I, Johnston BL. 2014. Lyme disease: clinical diagnosis and treatment. Can Commun Dis Rep 40(11):194–208, PMID: 29769842, https://doi.org/10.14745/ccdr.v40i11a01.
7. Aucott JN, Yang T, Yoon I, Powell D, Geller SA, Rebman AW. 2022. Risk of post-treatment Lyme disease in patients with ideally-treated early Lyme disease: a prospective cohort study. Int J Infect Dis 116:230–237, PMID: 35066160, https://doi.org/10.1016/j.ijid.2022.01.033.
8. Ogden NH, Bouchard C, Badcock J, Drebot MA, Elias SP, Hatchette TF, et al. 2019. What is the real number of Lyme disease cases in Canada? BMC Public Health 19(1):849, PMID: 31253135, https://doi.org/10.1186/s12889-019-7219-x.
9. Ogden NH, Lindsay LR, Hanincová K, Barker IK, Bigras-Poulin M, Charron DF, et al. 2008. The role of migratory birds in introduction and range expansion of *Ixodes scapularis* ticks, and *Borrelia burgdorferi* and *Anaplasma phagocytophilum* in Canada. Appl Environ Microbiol 74(6):1780–1790, PMID: 18245258, https://doi.org/10.1128/AEM.01982-07.
10. Ogden NH, Bouchard C, Kurtenbach K, Margos G, Lindsay LR, Trudel L, et al. 2010. Active and passive surveillance, and phylogenetic analysis of *Borrelia burgdorferi* elucidate the process of Lyme disease risk emergence in Canada. Environ Health Perspect 118(7):909–914, PMID: 20421192, https://doi.org/10.1289/ehp.0901766.
11. Leighton PA, Koffi JK, Pelcat Y, Lindsay LR, Ogden NH. 2012. Predicting the speed of tick invasion: an empirical model of range expansion for the Lyme disease vector *Ixodes scapularis* in Canada. J Appl Ecol 49(2):457–464, https://doi.org/10.1111/j.1365-2664.2012.02112.x.
12. Ogden NH, Radojevic M, Wu X, Duvvuri VR, Leighton PA, Wu J. 2014. Estimated effects of projected climate change on the basic reproductive number of the Lyme disease vector *Ixodes scapularis*. Environ Health Perspect 122(6):631–638, PMID: 24627295, https://doi.org/10.1289/ehp.1307799.
13. Ogden NH, Lindsay LR, Leighton PA. 2013. Predicting the rate of invasion of the agent of Lyme disease, *Borrelia burgdorferi*. J Appl Ecol 50(2):510–518, https://doi.org/10.1111/1365-2664.12050.
14. Gabriele-Rivet V, Arsenault J, Badcock J, Cheng A, Edsall J, Goltz J, et al. 2015. Different ecological niches for ticks of public health significance in Canada. PLoS One 10(7):e0131282, PMID: 26131550, https://doi.org/10.1371/journal.pone.0131282.
15. Ebi KL, Ogden NH, Semenza JC, Woodward A. 2017. Detecting and attributing health burdens to climate change. Environ Health Perspect 125(8):085004, PMID: 28796635, https://doi.org/10.1289/EHP1509.
16. Ogden NH, Maarouf A, Barker IK, Bigras-Poulin M, Lindsay LR, Morshed MG, et al. 2006. Climate change and the potential for range expansion of the Lyme disease vector *Ixodes scapularis* in Canada. Int J Parasitol 36(1):63–70, PMID: 16229849, https://doi.org/10.1016/j.ijpara.2005.08.016.
17. McPherson M, García-García A, Cuesta-Valero FJ, Belltrami H, Hansen-Ketchum P, MacDougall D, et al. 2017. Expansion of the Lyme disease vector *Ixodes scapularis* in Canada inferred from CMIP5 climate projections. Environ Health Perspect 125(5):057008, PMID: 28599266, https://doi.org/10.1289/EHP57.
18. Boyd R, Eyzaguirre J, Poulsen F, Siegle M, Thompson A, Yamamoto S, et al. 2020. *Costing Climate Change Impacts on Human Health Across Canada*. Prepared by ESSA Technologies Ltd. for the Canadian Institute for Climate Choices. https://choixclimatiques.ca/wp-content/uploads/2021/06/ESSA-Technical-Report-March2021.pdf [accessed 9 January 2024].
19. Nelson CA, Saha S, Kugeler KJ, Delorey MJ, Shankar MB, Hinckley AF, et al. 2015. Incidence of clinician-diagnosed Lyme disease, United States, 2005–2010. Emerg Infect Dis 21(9):1625–1631, PMID: 26291194, https://doi.org/10.3201/eid2109.150417.
20. Kugeler KJ, Schwartz AM, Delorey MJ, Mead PS, Hinckley AF. 2021. Estimating the frequency of Lyme disease diagnoses, United States, 2010–2018. Emerg Infect Dis 27(2):616–619, PMID: 33496229, https://doi.org/10.3201/eid2702.202731.
21. Rice DP. 2000. Cost of illness studies: what is good about them? Inj Prev 6(3):177–179, PMID: 11003181, https://doi.org/10.1136/ip.6.3.177.
22. Haines A. 2017. Health co-benefits of climate action. Lancet Planet Health 1(1): e4–e5, PMID: 29851591, https://doi.org/10.1016/S2542-5196(17)30003-7.
23. Statistics Canada. 2024. Census of Population. [Webpage.] Date modified 23 January 2024. https://www12.statcan.gc.ca/census-recensement/index-eng.cfm [accessed 9 January 2024].
24. U.S. Fish and Wildlife Service. 2011. U.S. Fish and Wildlife Service Landscape Conservation Cooperatives, vector digital data. https://www.sciencebase.gov/catalog/item/4fbbd87be4b0ee66f48f66f3 [accessed 9 January 2024].

25. Wilson CH, Gasmi S, Bourgeois AC, Badcock J, Chahil N, Kulkarni MA, et al. 2022. Surveillance for *Ixodes scapularis* and *Ixodes pacificus* ticks and their associated pathogens in Canada, 2019. Can Commun Dis Rep 48(5):208–218, PMID: 37325256, https://doi.org/10.14745/ccdr.v48i05a04.
26. Koffi JK, Leighton PA, Pelcat Y, Trudel L, Lindsay LR, Milord F, et al. 2012. Passive surveillance for *I. scapularis* ticks: enhanced analysis for early detection of emerging Lyme disease risk. J Med Entomol 49(2):400–409, PMID: 22493860, https://doi.org/10.1603/me11210.
27. Ogden NH, Trudel L, Artsob H, Barker IK, Beauchamp G, Charron DF, et al. 2006. *Ixodes scapularis* ticks collected by passive surveillance in Canada: analysis of geographic distribution and infection with Lyme borreliosis agent *Borrelia burgdorferi*. J Med Entomol 43(3):600–609, PMID: 16739422, https://doi.org/10.1093/jmedent/43.3.600.
28. Guillot C, Badcock J, Clow K, Cram J, Dergousoff S, Dibernardo A, et al. 2020. Sentinel surveillance of Lyme disease risk in Canada, 2019: results from the first year of the Canadian Lyme Sentinel Network (CaLSeN). Can Commun Dis Rep 46(10):354–361, PMID: 33315999, https://doi.org/10.14745/ccdr.v46i10a08.
29. Rand PW, Lubelczyk C, Lavigne GR, Elias S, Holman MS, Lacombe EH, et al. 2003. Deer density and the abundance of *Ixodes scapularis* (Acari: Ixodidae). J Med Entomol 40(2):179–184, PMID: 12693846, https://doi.org/10.1603/0022-2585-40.2.179.
30. Rand PW, Lubelczyk C, Holman MS, Lacombe EH, Smith RP Jr. 2004. Abundance of *Ixodes scapularis* (Acari: Ixodidae) after the complete removal of deer from an isolated offshore island, endemic for Lyme disease. J Med Entomol 41(4):779–784, PMID: 15311475, https://doi.org/10.1603/0022-2585-41.4.779.
31. Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, et al. 2020. The ERA5 global reanalysis. Q J R Meteorol Soc 146(730):1999–2049, https://doi.org/10.1002/qj.3803.
32. Mearns LO, McGuinness S, Korytina D, Scinocca J, Kharin S, Jiao Y, et al. 2017. The NA-CORDEX dataset, version 1.0. https://doi.org/10.5065/D6SJ1JCH [accessed 9 January 2024].
33. Lindsay LR, Barker IK, Surgeoner GA, McEwen SA, Gillespie TJ, Robinson JT. 1995. Survival and development of *Ixodes scapularis* (Acari: Ixodidae) under various climatic conditions in Ontario, Canada. J Med Entomol 32(2):143–152, PMID: 7608920, https://doi.org/10.1093/jmedent/32.2.143.
34. Ogden NH, Beard CB, Ginsberg H, Tsao J. 2021. Possible effects of climate change on Ixodid ticks and the pathogens they transmit: predictions and observations. J Med Entomol 58(4):1536–1545, PMID: 33112403, https://doi.org/10.1093/jme/tjaa220.
35. Ogden NH, Bigras-Poulin M, O'Callaghan CJ, Barker IK, Lindsay LR, Maarouf A, et al. 2005. A dynamic population model to investigate effects of climate on geographic range and seasonality of the tick *Ixodes scapularis*. Int J Parasitol 35(4):375–389, PMID: 15777914, https://doi.org/10.1016/j.ijpara.2004.12.013.
36. van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. 2011. The representative concentration pathways: an overview. Clim Change 109(1–2):5–31, https://doi.org/10.1007/s10584-011-0148-z.
37. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, et al. 2010. The next generation of scenarios for climate change research and assessment. Nature 463(7282):747–756, PMID: 20148028, https://doi.org/10.1038/nature08823.
38. Government of Canada. 2023. Lyme disease: surveillance. Date modified 4 December 2023. https://www.canada.ca/en/public-health/services/diseases/lyme-disease/surveillance-lyme-disease.html [accessed 9 January 2024].
39. Ogden NH, Lindsay LR, Morshed M, Sockett PN, Artsob H. 2009. The emergence of Lyme disease in Canada. CMAJ 180(12):1221–1224, PMID: 19506281, https://doi.org/10.1503/cmaj.080148.
40. Barker IK, Surgeoner GA, Artsob H, McEwen SA, Elliott LA, Campbell GD, et al. 1992. Distribution of the Lyme disease vector, *Ixodes dammini* (Acari: Ixodidae) and isolation of *Borrelia burgdorferi* in Ontario, Canada. J Med Entomol 29(6):1011–1022, PMID: 1460617, https://doi.org/10.1093/jmedent/29.6.1011.
41. Aenishaenslin C, Bouchard C, Koffi JK, Pelcat Y, Ogden NH. 2016. Evidence of rapid changes in Lyme disease awareness in Canada. Ticks Tick Borne Dis 7(6):1067–1074, PMID: 27665265, https://doi.org/10.1016/j.ttbdis.2016.09.007.
42. Curriero FC, Wychgram C, Rebman AW, Corrigan AE, Kvit A, Shields T, et al. 2021. The Lyme and Tickborne Disease Dashboard: a map-based resource to promote public health awareness and research collaboration. PLoS One 16(12):e0260122, PMID: 34851988, https://doi.org/10.1371/journal.pone.0260122.
43. Statistics Canada. 2018. Health Regions: Boundaries and Correspondence with Census Geography. Date modified 14 December 2018. https://www150.statcan.gc.ca/n1/pub/82-402-x/2018001/corr-eng.htm [accessed 9 January 2024].
44. CDC (US Centers for Disease Control and Prevention). 2022. Lyme disease surveillance data. https://www.cdc.gov/lyme/datasurveillance/surveillance-data.html [accessed 9 January 2024].
45. Institut national de santé publique du Québec. 2024. Résultats de surveillance de la maladie de Lyme: année 2019. https://www.inspq.qc.ca/zoonoses/maladie-de-lyme/resultats-de-surveillance-2019#:∼:text=Surveillance%20humaine,94%2D%2C84 [accessed 9 January 2024].
46. Nova Scotia Department of Health and Wellness. 2022. *Notifiable Diseases in Nova Scotia: 2020 and 2021 Surveillance Report*. https://novascotia.ca/dhw/populationhealth/documents/Annual-Notifiable-Disease-Surveillance-Report-2020-2021.pdf [accessed 9 January 2024].
47. Mac S, Evans GA, Patel SN, Pullenayegum EM, Sander B. 2021. Estimating the population health burden of Lyme disease in Ontario, Canada: a microsimulation modelling approach. CMAJ Open 9(4):E1005–E1012, PMID: 34785530, https://doi.org/10.9778/cmajo.20210024.
48. Ontario Ministry of Health and Long Term Care. 2022. Ontario Health Insurance Plan, schedule of benefits and fees - health care professionals. https://www.ontario.ca/files/2024-01/moh-ohip-schedule-of-benefits-2024-01-24.pdf [accessed 9 January 2024].
49. Canada Drugs Direct. 2024. Vibramycin hyclate (doxycycline hyclate). https://www.canadadrugsdirect.com/products/doxycycline-hyclate [accessed 9 January 2024].
50. Health Quality Ontario. 2018. Diagnosing and managing early Lyme disease in Ontario. https://www.hqontario.ca/Events/Diagnosing-and-Managing-Early-Lyme-Disease-in-Ontario [accessed 9 January 2024].
51. Shing E, Wang J, Khoo E, Evans GA, Moore S, Nelder MP, et al. 2019. Estimating direct healthcare costs attributable to laboratory-confirmed Lyme disease in Ontario, Canada: a population-based matched cohort study using health administrative data. Zoonoses Public Health 66(4):428–435, PMID: 30665259, https://doi.org/10.1111/zph.12560.
52. van den Wijngaard CC, Hofhuis A, Wong A, Harms MG, de Wit GA, Lugnér AK, et al. 2017. The cost of Lyme borreliosis. Eur J Public Health 27(3):538–547, PMID: 28444236, https://doi.org/10.1093/eurpub/ckw269.
53. Pike J, Grosse SD. 2018. Friction cost estimates of productivity costs in cost-of-illness studies in comparison with human capital estimates: a review. Appl Health Econ Health Policy 16(6):765–778, PMID: 30094591, https://doi.org/10.1007/s40258-018-0416-4.
54. van den Wijngaard CC, Hofhuis A, Harms MG, Haagsma JA, Wong A, de Wit GA, et al. 2015. The burden of Lyme borreliosis expressed in disability-adjusted life years. Eur J Public Health 25(6):1071–1078, PMID: 26082446, https://doi.org/10.1093/eurpub/ckv091.
55. Eisen L, Eisen RJ. 2023. Changes in the geographic distribution of the blacklegged tick, *Ixodes scapularis*, in the United States. Ticks Tick Borne Dis 14(6):102233, PMID: 37494882, https://doi.org/10.1016/j.ttbdis.2023.102233.
56. Dumic I, Severnini E. 2018. "Ticking bomb": the impact of climate change on the incidence of Lyme disease. Can J Infect Dis Med Microbiol 2018:5719081, PMID: 30473737, https://doi.org/10.1155/2018/5719081.
57. Ginsberg HS, Hickling GJ, Burke RL, Ogden NH, Beati L, LeBrun RA, et al. 2021. Why Lyme disease is common in the northern US, but rare in the south: the roles of host choice, host-seeking behavior, and tick density. PLoS Biol 19(1): e3001066, PMID: 33507921, https://doi.org/10.1371/journal.pbio.3001066.
58. Li S, Gilbert L, Vanwambeke SO, Yu J, Purse BV, Harrison PA. 2019. Lyme disease risks in Europe under multiple uncertain drivers of change. Environ Health Perspect 127(6):067010, PMID: 31232609, https://doi.org/10.1289/EHP4615.
59. Sellers S, Ebi KL. 2017. Climate change and health under the Shared Socioeconomic Pathway framework. Int J Environ Res Public Health 15(1):3, PMID: 29267204, https://doi.org/10.3390/ijerph15010003.
60. Statistics Canada. 2023. *Population Projections for Canada (2021 to 2068), Provinces and Territories (2021 to 2043): Technical Report on Methodology and Assumptions*. https://www150.statcan.gc.ca/n1/en/pub/91-620-x/91-620-x2022001-eng.pdf?st=4STi96Ht [accessed 9 January 2024].
61. McGirr A, Fisman DN, Tuite AR. 2019. The health and economic burden of pertussis in Canada: a microsimulation study. Vaccine 37(49):7240–7247, PMID: 31585727, https://doi.org/10.1016/j.vaccine.2019.09.070.
62. Tuite AR, Ng V, Ximenes R, Diener A, Rafferty E, Ogden NH, et al. 2023. Quantifying the economic gains associated with COVID-19 vaccination in the Canadian population: a cost-benefit analysis. Can Commun Dis Rep 49(6):263–273, https://doi.org/10.14745/ccdr.v49i06a03.
63. Ogden NH, Bouchard C, Brankston G, Brown E, Corrin T, Dibernardo A, et al. 2021. Infectious diseases. In: *Health of Canadians in a Changing Climate: Advancing Our Knowledge for Action*. Berry P, Schnitter R, eds., 366–467. https://changingclimate.ca/health-in-a-changing-climate/ [accessed 9 January 2024].
64. Crimmins A, Balbus J, Gamble JL, Beard CB, Bell JE, Dodgen D, et al. 2016. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. http://dx.doi.org/10.7930/J0R49NQX [accessed 9 January 2024].
65. United Nations Office for Disaster Risk Reduction. 2022. *Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future*. https://www.undrr.org/GAR2022 [accessed 9 January 2024].