Local landscape change, personal practices, and Lyme disease risk in Ottawa, Ontario

James Joseph Logan

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School of Epidemiology and Public Health
Faculty of Medicine
University of Ottawa

Abstract

In Canada, Lyme disease is an emerging tick-borne illness with a number and extent of risk areas that continue to expand due to the effects of climate change. Nationally, the incidence of Lyme disease increased more than 17-fold since its designation as a notifiable disease in 2009. While Ontario's incidence rate is one of the highest among Canadian provinces, Ottawa was declared an at-risk region for the first time in 2017. Amidst the emergence of reproducing blacklegged tick populations and continued urban expansion of new communities into natural areas throughout this municipal region, the local incidence of Lyme disease has more than tripled.

Using the municipal region of Ottawa as a study setting, the objective of my thesis was to examine local Lyme disease risk as a function of environmental hazard and population-level vulnerability. I achieved this by (1) exploring socioeconomic and landscape factors associated with local Lyme disease risk at the neighbourhood scale, (2) identifying population-level characteristics associated with high knowledge and protective behaviour adoption, and (3) examining the Lyme disease transmission risk across a gradient of residential to woodland land use.

Count models of Lyme disease cases arising from exposures within patients' home neighbourhoods highlighted associations between forested landscape configurations and elevated local risk. Analysis of survey results identified population-level characteristics and high levels of both knowledge regarding Lyme disease and adoption of preventive and protective behaviours, from which several dynamics among population and exposure risk subgroups emerged. Finally, an analysis of environmental hazard along the residential-woodland gradient in western Ottawa

neighbourhoods identified significant risk in the shared ecotone. Together, the results present strong evidence for factors associated with increased potential for human-tick encounters in fine-scale local settings and opportunities for targeted Lyme disease prevention efforts.

Thesis Supervisor

Dr. Manisha Kulkarni, PhD (Medical Entomology)

Associate Professor, School of Epidemiology and Public Health (SEPH), University of Ottawa

manisha.kulkarni@uottawa.ca

Thesis Advisory Committee (TAC)

Dr. Tim Ramsay, PhD (Epidemiologist and Biostatistician)

Associate Professor, School of Epidemiology and Public Health (SEPH), University of Ottawa

Senior Scientist, Ottawa Hospital Research Institute

tramsay@ohri.ca

Dr. Justine Blanford, PhD (Biologist and GIS Scientist)

Professor, Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, Netherlands

j.i.blanford@utwente.nl

Dr. Nicholas Ogden, PhD (Zoologist, Lyme disease ecology)

Senior Research Scientist and Director, Public Health Risk Sciences Division, National Microbiology Laboratory, Public Health Agency of Canada, Saint-Hyacinthe, Québec

nicholas.ogden@phac-aspc.gc.ca

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List of Abbreviations

AIC	Akaike Information Criterion
Bb	*Borrelia burgdorferi*
CI	Confidence interval
CLyDRN	Canadian Lyme Disease Research Network
CNDSS	Canadian Notifiable Disease Surveillance System
DIN	Density of Infected Nymphs
FSA	Forward Sortation Area
GEE	Google Earth Engine
GIS	Geographic Information System
GLM	Generalized Linear Model
IPCC	Intergovernmental Panel on Climate Change
iPHIS	Integrated Public Health Information System
IRR	Incidence Rate Ratio
IS	*Ixodes scapularis*
KAP	Knowledge, attitudes and practices
LD	Lyme disease
LDES	Lyme Disease Enhanced Surveillance
MAUP	Modifiable areal unit problem
NB	Negative Binomial
NML	National Microbiology Laboratory
ONS	Ottawa Neighbourhood Study

OR	Odds Ratio
PHAC	Public Health Agency of Canada
PMT	Protection Motivation Theory
PTLDS	Post-Treatment Lyme Disease Syndrome
RF	Random Forests
RR	Risk Ratio
SA	Spatial Autocorrelation
SD	Standard Deviation
VBD	Vector-borne disease

Chapter 1

Introduction

You explored a forest like this what seems hundreds of times in your childhood. Straight behind your backyard, or your grandparents'. You ran off, careened through the fallen leaves, scattering them in all directions in small explosions of brown, orange, yellow, red. Or no – you remember the same woods as lush and serene, the perfect place to listen to bird calls that changed with the season as you searched for the perfect fallen tree limb, lugged it, and propped it up against that old maple for one of a hundred attempts at your secret, sheltered hideaway. Every time you burst back through the underbrush just as the day cooled, grass, dirt and loose leaves cling to your clothing, prompting the inevitable call to wash up. And that was it. Wash, eat, sleep and repeat. This time? You ventured into the same type of woods, didn't wander nearly as deep, and certainly did no more than walk and enjoy the fresh air. Still – you look in the mirror and spot the blacklegged tick embedded just below your hairline. You knew to look for it. Somehow, this tiny invader makes the distant and familiar memory of your youth an alien experience. What changed, and why this once-unfamiliar mistrust of the woods?

The change occurred relatively recently. In the early 1990s, Long Point, Ontario, on the shore of Lake Erie, was the only known Canadian location with an established population of blacklegged ticks [1]. Throughout the next decade, reports of human Lyme disease (LD) cases and the advent

of passive tick surveillance signaled that tick populations had begun emerging in numerous regions across Canada - in Nova Scotia, New Brunswick, and across southern Ontario, Quebec, and Manitoba, [2,3]. Once Lyme disease was officially designated as a nationally notifiable disease in 2009, 144 human cases were reported in the following year. In the time since, public health officials have reported 17,080 human cases from across Canada, with the 2,168 cases reported in 2022 marking a fifteen-fold increase over the first year of reporting [4]. The rapid rise in Lyme disease incidence led the Government of Canada to identify the need for a consolidated approach to Lyme disease prevention, identification, treatment and management through guidance established under a 'Federal Framework on Lyme Disease Act,' which received Royal Assent in December, 2014 [5]. The report that emerged from this Act, 'Lyme Disease in Canada – A Federal Framework' was released in 2017 and identified a shared responsibility across multiple government agencies, including efforts to fund research addressing the emerging threat by the Public Health Agency of Canada (PHAC) and Canadian Institutes of Health Research (CIHR) [6].

My research activities fell under two ongoing projects – "Public health risk assessment tools for emerging vector-borne diseases", funded through a CIHR project grant, and "Best practices for urban planning in the context of climate change and emerging tick-borne diseases (UPTick)," funded by PHAC's Infectious Diseases and Climate Change Fund. Both projects were led by my thesis supervisor, Dr. Manisha Kulkarni, and involved collaborations with investigators from the Public Health Agency of Canada (Dr. Nicholas Ogden), the University of Montréal (Dr. Patrick Leighton), and the University of Ottawa's Department of Geography, Environment, and Geomatics (Drs. Anders Knudby and Michael Sawada) for various components. The main goal

of both projects was to use a One Health approach, exploring the connection between environmental and epidemiological risk, to better understand the socioecological drivers of Lyme disease risk at a local scale. Applying spatial and epidemiological analysis methods in a Canadian urban centre, these projects aimed to inform community-focused strategies for Lyme disease prevention, particularly in the context of changing urban landscapes. My role in these projects was to analyze human reportable disease and tick surveillance data within the City of Ottawa, perform active surveillance activities in field studies, and develop novel spatial risk models for LD.

My thesis investigates the risk of human tick-borne disease infection that arises from the presence of the tick vector, pathogen and wildlife hosts in the environment, and human activity that leads to encounters with ticks. It addresses critical public health issues regarding prevention and intervention, specifically in locations where the emergence of tick vector populations may lead to increases in peri-domestic tick encounters and tick-borne disease incidence. Through a One Health approach to LD risk – exploring human, environmental, and wildlife elements of tick-borne disease risk through multiple disciplines – the aim of my thesis is to contribute to our understanding of where and how the intersection of human activity with potential tick habitat results in elevated LD risk in the city of Ottawa, Canada, with the intention of generating results that may be applicable to other municipalities experiencing an emerging threat from tick populations.

1.1 Organization of the Thesis

Chapter 1: Introduction

The opening chapter of my thesis details my research objectives and connects them to the conceptual model that underpins my work. I go on to describe the epidemiology of Lyme disease, broadly, in Canada, and in closer detail in Ontario and the City of Ottawa, where my research activities took place. I also briefly discuss the existing evidence of climate change as a driver of the continued emergence and expansion of Lyme disease in these areas. Lastly, I provide an overview of the surveillance and research systems employed in Canada to monitor this public health threat.

Chapter 2: Background

The second chapter opens with fundamental information about the Lyme disease system, including the tick-borne transmission cycle of the *Borrelia burgdorferi* pathogen that causes human Lyme disease. I also briefly review the available literature with respect to the lifecycle, phenology, and ecology of *Ixodes* scapularis (the "blacklegged" tick), which is relevant to the fieldwork activities conducted during my research. Finally, to explain the effects of landscape factors on disease risk that are the central tenet explored throughout my thesis, I present an overview of the current evidence encompassing forest fragmentation and land cover effects on environmental Lyme disease risk.

Chapter 3: Methods

While specific details on study design and data analysis approaches will be found under the respective articles of my thesis, I use this third chapter to present a contextual overview for the

methods used throughout. First, I describe the study area to illustrate the distinctive geography which provides context for my research findings. I also briefly identify the various data sources, noting in which chapter they are described fully. I continue to present details of the spatial and remote sensing methods, data processing, regression models and their underlying statistical distributions, as well as the rigorous fieldwork approach undertaken in my research.

Chapters 4-6: Articles

The following three chapters each present a manuscript describing the work that was completed under each objective. Each of these chapters is prefaced with a brief description, an article citation where appropriate, coauthor contributions, and a statement of the ethical approvals obtained. In my first article, published in PLOS One, I developed landscape metrics using high-resolution satellite imagery and applied these using spatial negative binomial regression models to identify associations between neighbourhood landscape and within-neighbourhood human Lyme disease incidence. In my second article, published in BMC Public Health, I designed and analyzed responses from a cross-sectional survey of Ottawa adults to identify characteristics associated with (a) possessing a high level of knowledge regarding Lyme disease, and (b) adoption of a high number of protective practices or behaviours. My third article, published in Scientific Reports, examines the effect of landscape types at different stages of urban development (e.g., 'residential', 'woodland', and 'interface') on nymphal tick abundance and presence of infected ticks as measures of Lyme disease environmental risk, controlling for factors of the microhabitat known to influence tick ecology and survival. This manuscript provides an examination of local-scale factors in settings where tick habitat and human activity

intersect, which are seldom explored in the literature, but are important to consider as new communities experience tick invasion and establishment.

Chapter 7: Integrated discussion

In this final chapter, I summarize my key research findings and discuss how these findings, as a whole, add to the body of knowledge regarding Lyme disease risk. I compare my findings to other research that has explored the risk of tick-borne disease present at the forests' edge and how these environments are particularly important to locations like Ottawa, Ontario, where the vector of disease is newly emergent. Finally, I present some limitations of the research activities and propose extensions of the work performed that will continue to expand on these findings through further research.

1.2 Objectives and Conceptual Framework

1.2.1 Thesis objectives

The overall goal of my thesis was to identify and quantify the impacts that urban landscape change and human interaction with greenspace have on human Lyme disease risk. With the focus of this research on a region experiencing emerging blacklegged tick populations and rising Lyme disease incidence, the aim was to identify critical gaps at a local scale that would inform urban development and public health approaches for the prevention and control of Lyme disease risk.

My thesis contributes to the field of tick-borne disease research that seeks to improve prevention and risk reduction efforts, through a focus on understanding how continued environmental and

human changes affect the potential for human-tick encounters that may lead to Lyme disease exposure. As depicted in Figure 1.1, my thesis explores interdisciplinary methodologies in spatial epidemiology, population research, and disease ecology to evaluate local risk in peri-urban settings of Ottawa, Ontario. I focus on these areas because individual risk for Lyme disease is dependent on the coincidence of two factors: first, the presence of both the pathogen and vector of disease; and second, the human activity that leads to tick encounters and transmission opportunities.

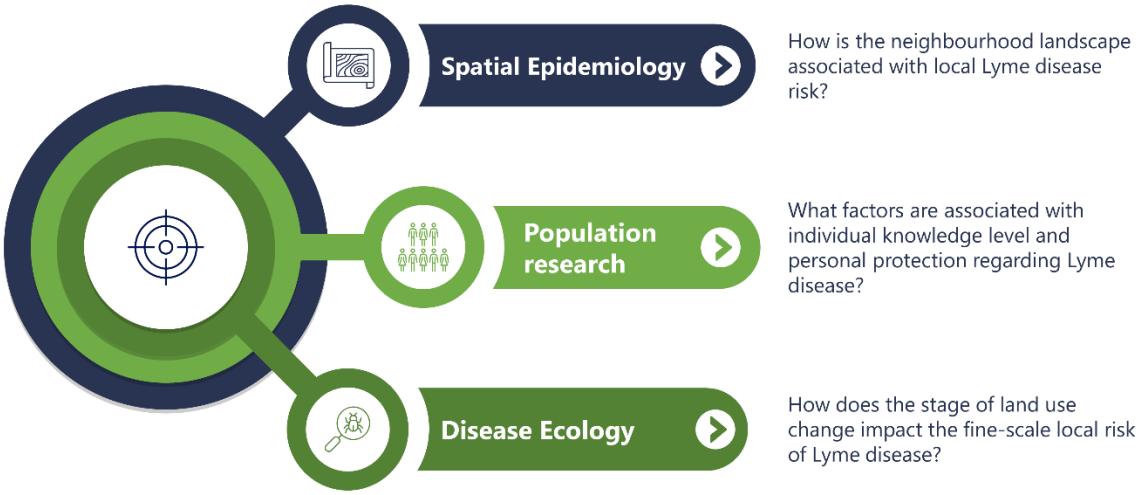


Figure 1.1 Research questions addressed by interdisciplinary approach of thesis

I examine the local effects that take part in this interaction through three specific objectives, which are addressed as independent articles within this dissertation:

1. To identify socioeconomic and environmental drivers of local Lyme disease risk at the neighbourhood geographic scale across Ottawa, Ontario.
2. To understand the level of knowledge, attitudes, and adoption of personal practices regarding Lyme disease among adults of Ottawa, Ontario.
3. To assess the impact of landscape change on Lyme disease transmission risk in peri-urban settings.

1.2.2 Conceptual framework

The objectives comprising my thesis are underscored by the conceptual model depicted in Figure 1.2, which is adapted here from the risk model for malaria first posited by Kienberger and Hagenlocher [7]. Initially conceived to align with the recommendations of the United Nations' Intergovernmental Panel on Climate Change (IPCC), this model centers on the premise that the risk of vector-borne diseases (VBD) rises from a coupled relationship between hazard (environmental factors) and vulnerability (social factors) [7,8]. Under this model, for vector-borne diseases, "hazard" is defined by the spatiotemporal presence of both vector and pathogen in the environment that contributes to the potential for human exposure. To the authors, this meant extant conditions that, left unmitigated, could develop into future threats [7]; however, it applies more generally to characterize current disease risks. "Vulnerability," on the other hand, is a social-driven function that comprises "the characteristics and actions of the vulnerable populations themselves" [7]. As such, in a given location with VBD hazard present, an individual's risk is influenced by their susceptibility; in the same location, the individual's behaviour contributes to resilience that reduces their personal level of risk. This opposition of

susceptibility and resilience as forces on individual vulnerability evokes the pressure and release idea of risk developed by Wisner et al. – while risk (pressure) builds due to the concomitant processes of hazard and vulnerability, the pressure can be relieved (i.e., risk reduced) through actions that build resilience and thereby reduce vulnerability [9].

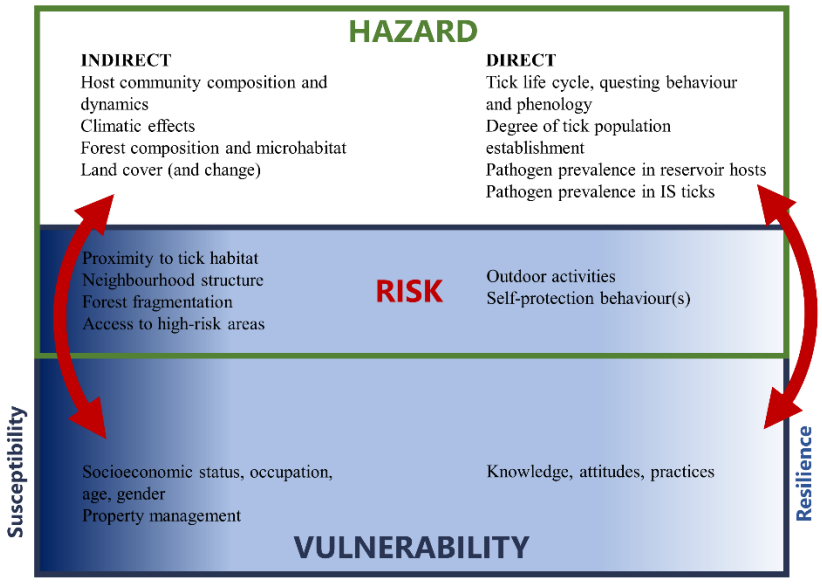


Figure 1.2 Conceptual framework for risk of tick-borne illness. IS = *Ixodes scapularis*.

Applied to the specific context of Lyme disease, hazard is represented by entomological indices (e.g., density of infected nymphs (DIN)) and the environmental factors unique to a geographic area (e.g., the suitability of a site for tick survival) [10–12]. In Lyme disease research, DIN is most often used to approximate local hazard as the nymphal tick stage is considered the greatest threat to human infection, due to (1) its activity during warmer months when people engage in

outdoor activities; and (2) their small size, which often contributes to non-detection and prolonged attachment to the host, in turn leading to greater probability of pathogen transmission [13]. Vulnerability to Lyme disease is determined by sociodemographic and behavioural factors, such as socioeconomic status, proximity, access to, and use of 'hazardous' areas, and personal practices adopted to avoid or minimize exposure (i.e., tick bites), as well as biological susceptibility [14,15]. Taken together, Lyme disease risk estimates the potential for human activity to result in exposure to and infection with the *B. burgdorferi* bacterium through the bite of an infected tick.

My conceptual model also adopts elements of the theoretical framework used by Fischhoff, Keesing, and Ostfeld to identify direct and indirect factors involved in the causal relationships that result in Lyme disease [14]. Under this framework, the outcomes of tick bites and *B. burgdorferi* infection result from the direct risk posed by entomological hazard, or the abundance of ticks in an area that are infected with pathogens that may affect humans (often called environmental risk), and the human activities and self-protection behaviours that reduce vulnerability. The probability of tick encounters resulting in infection is driven by the interaction of these direct factors. While other factors, such as land cover and host species communities are considered indirect under this model, they have a significant and influential role in the lifecycle and transmission dynamics that enhance the probability for the direct factors that give rise to Lyme disease outcomes. Though host susceptibility due to biological factors (e.g., age, sex, immune status) is also important in determining the likelihood of infection and clinical disease following exposure, this aspect of vulnerability is not the focus of this thesis.

1.2.3 Linking the conceptual framework to thesis objectives

The conceptual framework was used to guide my thesis research in order to evaluate the impacts of human-driven landscape changes and individual activities in the peri-urban environment on Lyme disease risk. My first objective is an ecological analysis of the association between neighbourhood structure, including the integration of residential zones with woodlands, and the local epidemiological risk of Lyme disease. This will contribute to an improved understanding of the regional epidemiology of Lyme disease transmission in Ottawa and eastern Ontario.

To address my second objective, I conducted a cross-sectional survey of knowledge, attitudes, and practices (KAP) regarding Lyme disease to establish the population level of Lyme disease vulnerability among Ottawa adults. This objective contributes to the assessment of local risk by characterizing the perception of peridomestic and residential risk among Ottawa adults. With the survey instrument I also collected information on where respondents engage in woodland activities and how far they travel to areas that pose high LD risk. This information provides a valuable perspective into the travel patterns and potential exposure locations for Ottawa residents, given that many cases reported to Ottawa Public Health are presumed to occur outside of the city [16,17].

My third and final objective examines the coupling of hazard and vulnerability by evaluating the different stages of land development that often occur through the encroachment of new housing developments into woodland areas. Other studies have separately demonstrated the effects of forest fragmentation and forest edge effects, such as the shared edge between forests and urban parks, on the hazard posed by tick populations. Establishing the presence and magnitude of forest

edge effects at the interface with residential land cover may provide important considerations for urban planning in areas of municipal expansion, and inform public health communication and disease prevention efforts.

Below I present a summary of these objectives, a general description of the data sources used, outcomes of interest, and my analytic approach (Table 1.1).

Table 1.1 Summary of data sources, outcomes evaluated, and analytic approach for each thesis objective.

Objective	Data sources	Outcome of interest	Analytic approach
1	Reportable disease surveillance data from Ottawa Public Health, PlanetScope multispectral image tiles, Ottawa Neighbourhood Study boundaries and socioeconomic attributes	Local Lyme disease incidence	Negative binomial regression model to identify neighbourhood landscape factors (i.e., forest measurements, socioeconomic status) associated with local LD incidence
2	KAP survey of Ottawa adults	• High Lyme disease knowledge • High adoption of Lyme disease protective behaviours	Logistic regression model to identify population characteristics associated with high knowledge and adoption of personal practices regarding Lyme disease
3	Active tick surveillance data, field sampling and monitoring data for selected wildlife host species, environmental measures	• Abundance of nymphal ticks, ticks of all life stages • Presence of infected nymphal	Nested hierarchical negative binomial, logistic regression models to evaluate the effect of land at different stages of development

		ticks, ticks of all life stages	on the abundance and infection prevalence among nymphal ticks across sites

1.3 Emergence of Lyme disease in Canada

1.3.1 Lyme disease

Lyme disease is a vector-borne disease caused by the spirochete bacterium *Borrelia burgdorferi* (*Bb*), transmitted to humans through the bite of an infected tick [18]. Globally, four Ixodid ticks serve as the vector of *Bb* to humans – *Ixodes scapularis* in eastern North America, *I. pacificus* in western North America, *I. ricinus* in Europe, and *I. persulcatus* in Asia [19]. Each Ixodid species has a lifecycle comprised of larvae, nymph, and adult feeding stages. Ticks first acquire *Bb* in their larval or nymphal stage via a blood meal obtained from small wildlife hosts that serve as reservoirs for *Bb* (e.g., rodents, birds, some lizards), as vertical transmission of the bacterium from infected female ticks to their progeny is near-zero [20]. After a single blood meal, the tick drops off its host and moults into its next stage (larvae and nymphs) or reproduces before dying (adult males and females). The nymphal life stage is considered to be the biggest public health risk to humans because larval ticks are uninfected and only become infected via their first blood meal while adults are larger and more easily detected; nymphal ticks are more likely to go unnoticed and unremoved before they can transmit the bacterium [13,21]. After infection, clinical presentation in humans can include a wide range of symptoms, including a typical "bullseye rash" (erythema migrans), joint pain, and flu-like symptoms (i.e., headache, fever, fatigue) and can progress to serious cardiac, neurologic, or musculoskeletal manifestations if left untreated [22].

Lyme disease is the most common vector-borne disease in North America, with approximately 30,000 cases reported annually in the United States alone [23]. Even this number is considered an underestimate of the true impact of Lyme disease. Disease surveillance in the United States relies on passive reporting of positive cases yet the true number of cases is likely much higher, as the CDC reports 476,000 Americans are treated for Lyme disease each year [24,25] with the expectation that some cases still go undetected. Findings in Canada suggest that only one third of the cases occurring in areas of Lyme disease emergence are reported [26]. In areas with a long history of endemicity for ticks and Lyme disease, the precise location of human encounters with host-seeking ticks is one of the most poorly understood components of Lyme disease incidence [21]. Not only is there inconsistency in the literature about the most common site of exposure – residential or otherwise – but the proportion of Lyme disease patients who are aware of their tick bite at all ranges widely (14-67%) [21]. With such uncertainty in the estimated burden that Lyme disease can have on healthcare systems, it is vital to identify areas at risk and establish effective methods for prevention and control.

1.3.2 Climate change and Lyme disease

The expanding geographic extent of Lyme disease risk areas directly follows the rapid northward expansion of blacklegged tick populations. This process has occurred over the past three decades, leading to the gradual invasion of southern Canada from long-established tick populations in northern areas of the United States [27]. The phenomenon most responsible for this northward progression of the Lyme disease vector is climate change. Ticks thrive in a ‘Goldilocks zone’

where the climate is warm and humid, only emerging to seek hosts if it is not too hot or too cold. Though they are inured to inhospitable weather by their physiology and host-seeking behaviour, extreme conditions can increase their mortality in many locations. For example, while moulted nymphal and adult female *I. scapularis* ticks overwinter within leaf litter and emerge in spring to quest for their next blood meal, extreme cold (i.e., -20°C) can be lethal [28,29]. Recent projections suggest that the range of suitable tick habitats is expanding into more regions of Canada and may extend by approximately 35 to 55 kilometres annually due to the rate of climate change [30–33]. The vector's encroachment is tangible at the local scale; studies continue to offer evidence for the presence of *I. scapularis* ticks where they were not previously found [34,35]. Furthermore, Canadian projections informed by these models point to substantial increases in the incidence and cost of Lyme disease, driven by the rate of tick population emergence in densely populated regions under even the most conservative climate change scenarios [36].

1.3.3 Epidemiology of Lyme disease in Canada

In Canada, Lyme disease first became nationally notifiable in 2009, identifying it as a priority for public health surveillance. One year prior, the incidence of potentially autochthonous cases (where a tick encounter resulting in transmission most likely occurred within Canada) was roughly equal to that of travel-related cases [37]. In the fourteen years since, the number of cases has risen dramatically, from 144 in the first year of surveillance to 2,168 in preliminary data for 2022 [4]. Today, there is still considered to be significant under-reporting of Lyme disease in Canada. In 2021, Ontario, Nova Scotia, and Québec accounted for more than 95% of all

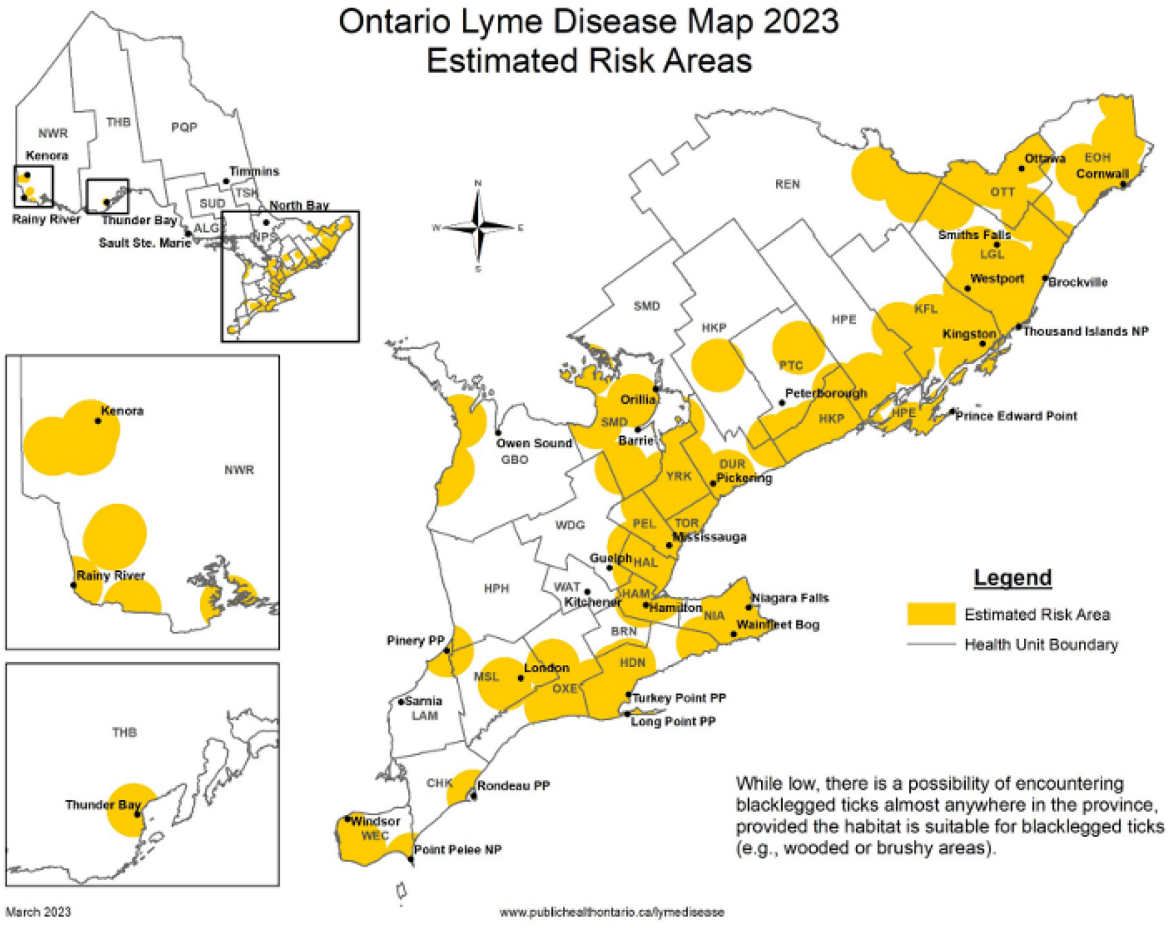
Canadian cases [38]. Nova Scotia exhibited the highest incidence of all ten provinces, with 60 per 100,000 population – more than seven times greater than the national incidence (8.2 per 100,000 population) [38]. However, incidence rates are often much higher among individual health units; province-wide rates tend to be lower due to the lesser establishment of tick populations at more northern latitudes. Travel history was available for nearly 80% of reported 2021 cases, and of these, nearly all occurred within Canada; almost all travel-related cases were reported by three provinces (Alberta, Saskatchewan, and Prince Edward Island) with no cases resulting from local transmission [38]. These trends in endemic cases are similar to the national patterns observed in emergent *I. scapularis* populations and *B. burgdorferi* infection rates [2,39,40].

Canadian cases of Lyme disease can occur in every month of the year. However, most reported disease onsets occur between the months of May and November with a peak in reporting activity in July (36%) [38]. This seasonality of disease occurrence corresponds directly to the period during which both nymphal ticks and humans engaging in outdoor activities are most active [41]. However, local climatic patterns can impact the early or delayed emergence in the period of peak tick activity, requiring increased public health awareness even in typically cooler months [42,43].

1.3.4 Epidemiology of Lyme disease in Ontario

In 2022, Public Health Ontario reported 1,490 Lyme disease cases, representing a rate of nearly 10 cases per 100,000 population [44]. Evidence supports the rapid range expansion of *I. scapularis* tick populations across southern, central and eastern Ontario, suggesting that

estimated risk areas continue to expand further northward within the province, as indicated in Figure 1-3 [34,45]. Recent studies focusing on spatial patterns in case reporting identify clusters of high disease incidence in several municipalities along the St. Lawrence Seaway and progressing northward to the Ottawa region [46,47]. Health units in these areas also reported the highest incidence rates in the province for 2022: 165.2 per 100,000 population in Kingston, Frontenac and Lennox & Addington; 58.6 per 100,000 population in Hastings Prince Edward; 55.9 per 100,000 population in Leeds, Grenville & Lanark; and 32 per 100,000 population in the Eastern Ontario unit [48].



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332 **Figure 1.3** Estimated Lyme disease risk areas in Ontario, 2023 [45]

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334 **1.3.5 Epidemiology of Lyme disease in Ottawa**

335 Locally, the municipality of Ottawa was declared an at-risk area for Lyme disease by public
336 health officials in 2017. During the period that LD has been nationally notifiable, the number of
337 cases reported to Ottawa Public Health rose from 6 in 2008 to 221 in 2022, with the city-wide
338 incidence rate per 100,000 population holding above 20 for each of the past two years [16].
339 Public health officials indicate that 51% of reported cases in 2018 were exposed to ticks in
340 locations outside of Ottawa [16]. However, neighbourhoods in western Ottawa show high rates

of local transmission, highlighted by clusters of cases with no connection to travel outside of the city [46].

1.3.6 Risk factors for Lyme disease

Most epidemiological studies on Lyme disease explore potential risk factors in settings across the United States or Europe with few focusing on factors driving the emerging threat in the Canadian context. As described above in the conceptual model, Lyme disease risk can be divided into components characterized by environmental hazard and population vulnerability. Following this, there are numerous types of risk factors associated with Lyme disease incidence that are related to each of these components of risk. Demographic factors associated with increased risk of Lyme disease tend to be age (e.g., children younger than 14 years and adults 55 or older), sex (i.e., males), and ethnicity (i.e., White) [14,38,46,49,50]. Several studies have also drawn connections between higher socioeconomic status and incidence of Lyme disease [46,51–53]. These characteristics are typically associated with human behaviours and activities that contribute to vulnerability and lower resilience, and thus increase the probability of exposure and transmission of the LD pathogen. Pet ownership, outdoor occupations, the use of personal protective measures, and activities in outdoor spaces (e.g., hiking, gardening) are associated with higher likelihood of LD infection [50,54]. However, the contribution to risk from outdoor activity and the adoption of protective practices can still vary between endemic areas [55].

As there is a high level of uncertainty in the most common geographic locations of tick bite encounters, factors that influence LD hazard are often considered at several spatial scales (e.g., personal property, local neighbourhoods, and regional landscapes). A considerable body of

evidence exists that connects attributes of residential properties with both LD vulnerability [55] and hazard [56]. Other studies look more broadly at regional landscapes to determine the contribution to LD hazard made by the fragmentation and configuration of forests, with contrasting arguments regarding its significance [53,57,58]. A recent meta-analysis conducted by Fischhoff et al. evaluated studies performed at each spatial scale and determined that risk factors at the neighbourhood scale (within 500 metres of the residential property) best explained the incidence of LD cases [15].

Still, much of this evidence comes from highly endemic areas in the United States where it is generally accepted that most tick bite exposures occur on residential yards or in personal gardens. In Canada, where blacklegged tick populations continue to intensify and spread, it is important to increase community awareness of the increasing risk in a variety of settings. Research contributions that focus on the changing rate of locally exposed LD cases and the factors involved at all spatial scales are crucial to improving the way we understand and communicate the risk present in peri-urban areas.

1.4 Canadian surveillance for Lyme disease

Surveillance for Lyme disease in Canada takes a “One Health” approach, wherein reportable disease data is complemented by the monitoring of tick presence and abundance in the environment. Together with targeted public health and research efforts to understand *B. burgdorferi* infection prevalence among wildlife host species, surveillance activities can provide a full picture of the burden and trends of Lyme disease emergence across Canadian geographies.

1.4.1 Notifiable disease surveillance

In Canada, public health units report human cases of Lyme disease to provincial and territorial health agencies, which in turn report to PHAC through the Canadian Notifiable Disease Surveillance System (CNDSS). From 2009 to 2011, CNDSS submissions included age, sex, and whether the case was probable – determined by clinical criteria alone – or confirmed by laboratory tests for each patient. After this time, PHAC collaborated with public health partners at multiple governmental levels to implement the Lyme Disease Enhanced Surveillance (LDES) system to expand the data shared through the CNDSS to include geography of exposure, clinical presentation, and laboratory test results, which added value by enabling pan-Canadian insights on LD incidence and risk areas [38].

Human disease surveillance provides evidence of the emerging trends in LD incidence in different regions of Canada. Evidence suggests that, in regions experiencing blacklegged tick emergence, there is a three- to five-year lag between tick invasion and spread of the *B. burgdorferi* pathogen [59]. In the context of continued range expansion of the Lyme disease vector, it is necessary to enhance the identification of areas with established and endemic LD risk in Canada.

1.4.2 Passive tick surveillance

Passive tick surveillance involves the submission of ticks of all feeding stages by members of the public who have found the specimens attached to themselves, family members, or pets, to

medical/veterinary practitioners or local public health authorities. A Canadian passive tick surveillance program was launched in the early 1990s to monitor for the presence of *I. scapularis* and *I. pacificus* ticks and the emergence of any potential tick-borne pathogens [2]. Under this program, submissions included the name of the location where the tick was found, the host species, the date of collection, and any travel history. Submitted ticks could also be forwarded to the National Microbiology Laboratory (NML) branch of PHAC to test for tick-borne pathogens [2,60]. Though programs in some regions were discontinued in recent years, some submissions are still provided by public health units to NML or university labs which contribute to pathogen testing efforts in order to monitor for newly-emerging tick species and tick-borne pathogens of public health significance [60]. Passive surveillance is commonly used to identify locations where ticks may occur and inform how their range and habitat may be evolving. However, while it is useful as an early signal for tick population establishment, passive surveillance is not suitable for estimating tick densities and locations of reproducing populations due to adventitious ticks which are dispersed widely by migratory birds [61]. Over the past decade, numerous provinces embraced and promoted eTick (https://www.etick.ca), a citizen science platform launched by Bishop's University where users submit photos of collected ticks for identification, as a prominent tool in passive surveillance activities. While this method, like the national program, is adequate for identifying the geographic occurrence of blacklegged ticks, it does not reliably predict spatial patterns of LD incidence [62].

1.4.3 Active tick surveillance

Active tick surveillance involves collecting ticks directly from the environment using a standardized method. This can take several forms - drag sampling (pulling a 1-m^2 white cloth along the ground), flag sampling (sweeping a 1-m^2 white cloth through denser underbrush), or capturing and examining host animals for ticks [60,63]. These field-based methods of surveillance are considered ideal to identify established or establishing populations of *I. scapularis* ticks and the potential for Lyme disease to become endemic in a specific locality [61]. To determine whether an area is at-risk, sites are selected based on broad zones of *I. scapularis* emergence signaled by passive surveillance results. Once sites are selected, standardized approaches to active surveillance are used to obtain reliable tick occurrence data. In Ontario, this involves multi-person teams dragging for a specified amount of person-time at each location over multiple site visits at times when conditions are optimal for the questing behaviour of ticks seeking their next blood meal (e.g., not during rain or when vegetation is wet from dew, in late morning or afternoon when temperatures are more suitable) [64]. According to Canadian public health guidelines, all three tick life stages must be detected for two successive years to designate a locality as endemic for Lyme disease risk, making such precise local estimates necessary to adequately inform where the public is at-risk [65]. While this approach can generate estimates of tick density and infection prevalence in local environments [31], it is highly resource-intensive, especially when performed at high spatial and temporal resolutions to achieve the most sensitive study design [39].

1.5 Chapter Summary

The goal of this thesis is to improve the understanding of the fine-scale impacts that urban development has on Lyme disease risk, specifically focusing on Ottawa, Ontario, a region undergoing tick population emergence. Through an interdisciplinary methodology, I aimed to identify factors that influence both the hazard of and vulnerability to tick-borne diseases present in a Canadian region affected by tick range expansion. Achieving these goals will advance knowledge on Lyme disease risk in Canadian urban centres and peri-urban settings, and may help to inform LD risk management approaches through improved public health and urban planning approaches that account for the continued climate-driven spread of blacklegged tick populations to new areas.

1.6 Chapter References

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Chapter 2

Background

2.1 Lyme Disease

Lyme disease is a bacterial infection in humans caused by a member of the *Borrelia burgdorferi sensu lato* (s.l.) species complex, acquired through the bite of an infected Ixodid tick. It is the most common tick-borne illness occurring in North America, Europe, and Asia, with ecology and epidemiology specific to each of these regions [1]. Lyme disease is an inflammatory disorder that, if detected and treated in its early stage, can manifest as relatively minor symptoms, with most diagnosed cases treated successfully through a course of antibiotics [2]. There are currently no vaccines available for humans which leaves control of human infections to interventions aimed at reducing environmental risk and personal preventive actions that reduce exposure opportunities [3].

2.1.1 Clinical presentation

Lyme disease commonly first presents as a "bulls-eye"-shaped skin rash, termed an erythema migrans (EM), at the site on the skin where the tick bite occurred. While this is the most recognizable clinical manifestation of *B. burgdorferi* infection, with roughly 80-90% of patients presenting an EM rash, the proportion of humans infected by *B. burgdorferi* who never develop an EM has been the subject of some dispute [4–7]. Still, alongside a captured Ixodid tick presented to clinicians to confirm exposure history, it is considered the sign with the most

diagnostic value for determining Lyme disease; other early symptoms of infection with BB include non-specific "flu-like symptoms" such as headache, fever, fatigue and malaise [8]. Later symptoms that may develop days to months after an infected tick bite include migratory pain in the joints, bones, tendons, and muscles; cognitive difficulty and/or memory loss; nerve pain or weakness; dizziness; severe headaches; irregular heartbeat; facial paralysis (Bell's palsy); or swelling of the brain [8,9]. These late-stage manifestations occur when *B. burgdorferi* affects specific bodily systems, the specifics of which are outside the scope of this thesis. In brief, they include: Lyme carditis (heart tissues), Lyme arthritis (joint tissues), Neurologic Lyme disease (central nervous system), and Post-Treatment Lyme Disease Syndrome (PTLDS; persistent auto-immune response after infection and treatment) [8,10,11].

2.1.2 Ecology of Lyme disease

Human Lyme disease risk relies on a multitude of complex, interwoven relationships between wildlife species, biotic and abiotic environmental factors, and their interplay with human development and activity. The probability of transmission to humans not only relies on the risk of exposure to ticks resulting in bites but also on the success of the bacterial spirochete being maintained and transmitted in the natural environment. To examine how this manifests with respect to human risk, I will present some points of consensus regarding the *Borrelia burgdorferi* transmission cycle in the wild, with a specific focus on northeastern North America.

2.1.2.1 Borrelia burgdorferi

In general, Lyme disease (termed Lyme borreliosis outside of North America) is caused by infection with a member of the *Borrelia burgdorferi* s.l. spirochete species complex [8,12]. In

North America, the illness is commonly caused by *Borrelia burgdorferi sensu stricto* (henceforth referred to as *B. burgdorferi* for brevity). In Europe, four additional *Borrelia* species cause human infection (i.e., *B. afzelii*, *B. garinii*, *B. spielmanii*, *B. bavariensis*), the diversity of which factor into observed differences in the clinical presentation reported in this region [8,13]. *B. burgdorferi* s.l. was likely present in the environment thousands of years ago, explaining the divergence between North American and European strains [14], but only became linked to human illness in the early 1980s [12].

2.1.2.2 Blacklegged ticks

There are four species of *Ixodes* ticks (Ixodidae) that act as the vector for *B. burgdorferi* around the world – *Ixodes scapularis* in eastern North America, *I. pacificus* in western North America, *I. ricinus* in Europe, and *I. persulcatus* in Asia [15]. All *Ixodes* ticks proceed through four developmental stages (instars): egg, larva, nymph, and adult. These species are three-host ticks, meaning each instar takes a blood meal from a new host, falling off after it becomes engorged and moulting into the next stage while on the ground or sheltered under vegetation or leaf litter [16]. Adult *Ixodes* do not moult after taking a full blood meal; females die following oviposition while males rarely feed and die shortly after mating on the host [16]. For *I. scapularis* ticks specifically, this cycle occurs over a two-year period (Figure 2.1). Each tick is a generalist ectoparasite, meaning that it does not have one specific or preferred host from which to take its three blood meals [1]. In fact, this lack of preference and selection from a wide variety of potential hosts is a key trait that lends to survival across developmental life stages through obligate blood-feeding. Larvae generally feed on small vertebrate animals, with small mammals

as the most frequent host though immature ticks feed on some birds and lizards as well [17,18]. While adults feed exclusively on medium and larger mammals [19], larval and nymphal ticks may be found on hosts of any size.

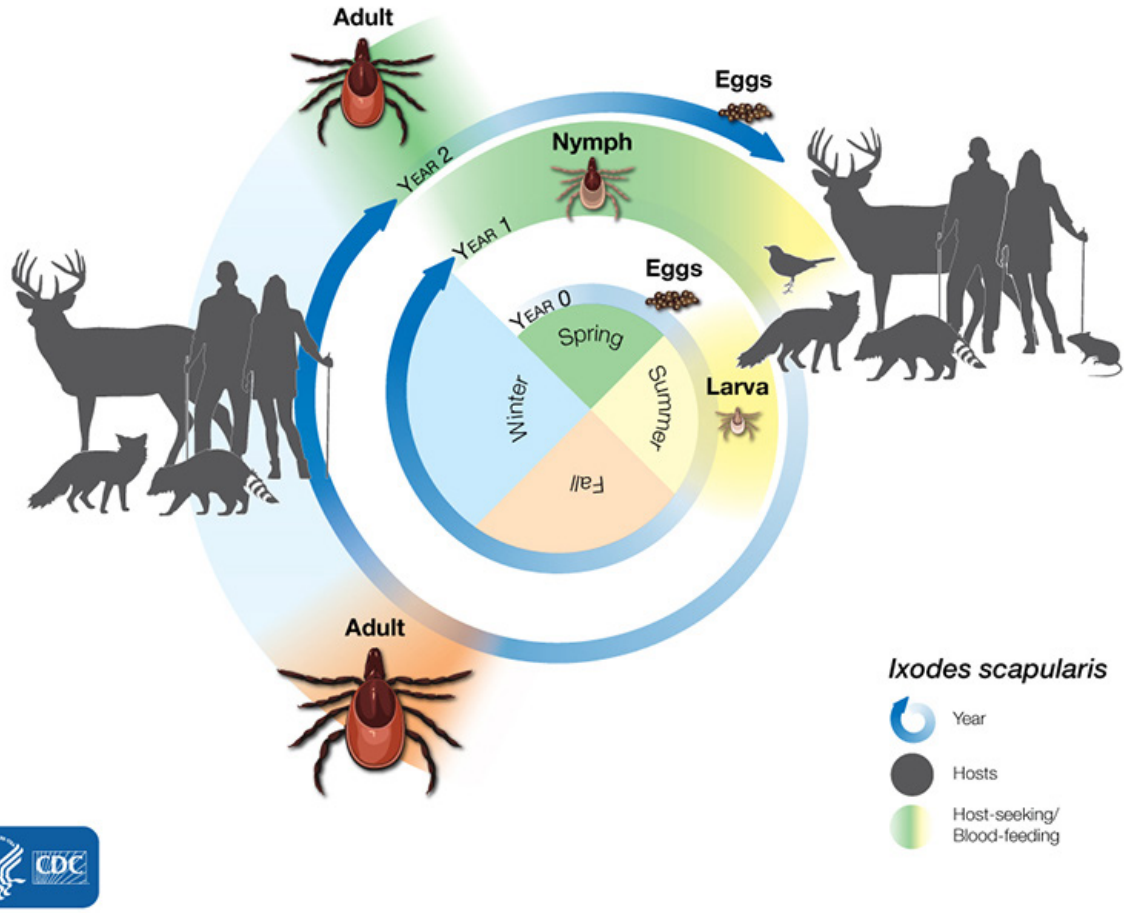

Figure 2.1 The biannual life cycle of *Ixodes scapularis* ticks. Image is originally prepared by Centers for Disease Control and Prevention, National Center for Emerging and Zoonotic Infectious Diseases (NCEZID), Division of Vector-Borne Diseases (DVBD) [16].

Figure 2.1 depicts the typical phenology of *I. scapularis* ticks in North America. Eggs deposited in the spring hatch into larvae at the oviposition site during the summer. Larvae then seek a blood

meal during the late summer or early fall and, once engorged, fall off their host [1]. Larval ticks may also enter diapause if conditions and host availability contribute to a failure to obtain a first blood meal, in which case they overwinter and attempt to feed again in the spring. For larvae that fed in the months immediately after they hatched and then overwintered, moulting into the nymph instar occurs in the late spring; those that overwintered before feeding moult during the summer, though mortality is greater among unfed overwintering larvae [20,21]. Some regional variability exists in the seasonality of larval activity due to differences in the biological rhythms of some tick populations with respect to diapause, host-seeking, and moulting. For example, in midwestern North America, where larval ticks more frequently enter behavioural diapause independent of climatic pressures, the seasonal activity of larvae occurs in two equally large peaks [22].

After the first moulting process, ticks emerge in their nymphal instar averaging less than 2 millimetres in size and actively host-seek from early May to late September with a peak of activity in mid-summer, though this timing can be dependent on latitude and geographical region [1,16]. When unable to successfully attach to a host, nymphs are the hardiest instar of blacklegged ticks. They can survive unfed 3 months longer, on average, than unfed adults [16]. Nymphs, like larvae, often complete a blood meal after 4 days but can take up to a week [23]. Their moulting process, which lasts approximately 40 days, also depends on the time of feeding – it occurs shortly after dropping off the host if the nymph feeds between April and July and follows overwintering if it acquires its blood meal in August or later in the year [23]. Overwintering has little effect on the proportion of nymphs that moult successfully, with evidence that factors other than climatic extremes have more association with nymphal mortality

[21,24]. While larvae do not directly contribute to LD risk due to the lack of vertical transmission of *B. burgdorferi* from adult females to eggs, transstadial survival of the pathogen in larvae means that the infection is retained after moulting [1,25]. Nymphal ticks, therefore, represent the most significant threat for transmission risk to humans, due to transstadial transmission, their small size, summer peak of activity, and feeding behaviours that are not preferential to host size.

Ticks that reach the adult stage are divided into two separate instars – males and females. Males tend to be marginally larger than nymphs at 2 mm in length and do not change in size after feeding. Females range in size from 2.4 to 2.7 mm when unfed but grow to as large as 10 mm after a complete blood meal, which lasts for a week on average [16,23]. After a 40-day nymphal moult, both adult instars typically emerge in September and are most active during October and remain so as long as temperature and precipitation do not force them into a period of quiescence. Adults that do not feed before they fall quiescent over the winter months re-emerge in early spring if they are not inhibited by snow cover or sub-zero temperatures [26,27]. Mating between male and female *I. scapularis* ticks frequently occurs on a large vertebrate host (e.g., white-tailed deer), either prior or concurrent to the female feeding, though it can sometimes occur off-host [16,28]. Male ticks mate with one or more females, may stay attached to the female throughout her feeding period, and die on the host after mating [28]. Once a mated female feeds fully, it drops from the host and lays several thousand eggs in late April or early May [21,29,30].

2.1.2.3 Questing behaviours of I. scapularis

Ticks of the Ixodidae family possess a pair of sensory structures, or Haller's organs, on their front legs that play a role in the olfactory perception of potential hosts and in sensing humidity, temperature, pheromones, and carbon dioxide [31]. Ixodes ticks climb grass or brush vegetation and wave their forelegs in the air for chemosensation, akin to insects using antennae, with the Haller's organs aiding the tick in detecting and orienting to nearby potential hosts in response to the above stimuli [16, 31[16,31]. Questing heights, or the vertical distance covered on vegetation before a tick commences this host-seeking behaviour, vary between life instars and Ixodidae species, with evidence that suggests geographically latitudinal differences as well [16,32,33].

Ambient air temperature and relative humidity at sites typically determine whether *Ixodes* ticks actively engage in host-seeking [20,34–36]. Studies of *I. scapularis* ticks in the United States demonstrate that individuals are induced to host-seeking within a range of 4 to 10 ℃ and tend to cease around 30 ℃ [35,36]. At the same time, local humidity determines the duration of questing by influencing the period of activity ticks can endure before needing to re-hydrate, as well as questing height [35]. Periods of low humidity can severely affect tick survival, by impacting the height above the refuge of leaf litter, where they retreat to rehydrate, they will venture [35,37,38]. Aridity further complicates survival for immature tick instars, forcing frequent retreats to leaf litter refuge that diminish their limited energy resources leading to starvation before they can attach to a host [37].

2.1.2.4 Influence of microhabitat factors on tick abundance

In Canada, Lindsay et al. demonstrated that habitat factors may influence the interstadial survival and host-seeking behaviour patterns of *I. scapularis* as much as the microclimatic factors identified previously [39]. Using field observations from four habitats of Long Point, Ontario, the authors identified that the density and distribution of leaf litter among habitats contribute to the overall survival and seasonal activity of ticks where they provide adequately humid refuges during periods of extreme climatic conditions. The indication that certain habitat types – for example, deciduous forests characterized by dense canopy contributing a substantial layer of leaf litter – are favourable for the expansion of tick populations is supported by studies in a variety of settings [40–44]. Forests dominated by tree species such as beech, oak, or maple, while contributing to the humid microclimate that aids tick resistance to desiccation also tend to be the preferred habitat for both reservoir and reproductive tick hosts [40,45].

2.1.3 Environmental Lyme disease risk in Ottawa, Ontario

Public health officials first declared Ottawa, Ontario an at-risk region for Lyme disease in 2017 [46]. Currently, maps published by Public Health Ontario identify much of the region extending east and west from Ottawa along the Ottawa River as falling within estimated Lyme disease risk areas [47]. In 2017, drag sampling of 23 sites distributed among municipal parks, trails, and forests of Ottawa revealed that blacklegged ticks were present at 70% of the sampled locations, with a nearly 30% infection prevalence of *B. burgdorferi* among those tested [48]. Further, longitudinal site surveillance between 2017 and 2019 indicates that stable, established populations of *I. scapularis* ticks are present predominantly in the western suburbs and rural

areas of Ottawa's municipal region, while populations are present and emerging in the east and south peri-urban sections of the city [49].

2.2 Association of landscape effects with human Lyme Disease risk

2.2.1 Impacts of landcover change

Lyme disease was originally discovered over forty years ago near Lyme, Connecticut [12]. Since its identification, historical evidence of the presence of *B. burgdorferi* in samples from 19th-century *P. leucopus* (white-footed mouse) museum specimens suggests that the discovery by Burgdorfer [12] may actually represent a re-emergence of the disease [50]. One hypothesis for this is that land use change trends in the intervening time have contributed to conditions suitable for sustained transmission cycles of *B. burgdorferi* in the wild while also increasing opportunities for human-tick encounters. This is due to a 'forest transition' that resulted from deforestation during early economic development in North America followed by forest cover resurgence as agricultural land use demands changed [51,52]. As the regrowth of woodlands occurred, cities in the United States also experienced the development of suburbs into the surrounding exurban regions recently reclaimed by forests [53,54].

This rise of the suburbs has contributed to a shrinking barrier between wildlife and humans, alongside a reduction in the variety of available tick hosts. Cities progressively expand outward and fragment woodlands that then mix with human habitation, resulting in dispersed habitat which favours reproductive tick hosts (e.g., white-tailed deer) and competent reservoir hosts (e.g., white-footed mice) [55]. As the suburbs and peri-urban regions continue to expand outward, enzootic transmission cycles occur in closer proximity to recreational and residential

spaces, increasing the likelihood of human-tick encounters and human infection [56,57]. While Lyme disease is newly-emerging in Canada, largely due to the introduction of adventitious ticks by migratory bird species and the shorter-range dispersal by deer and other large hosts, timely response and prevention strategies require recognition of the rise in risk associated with urban encroachment on natural areas seen in these endemic regions of the United States.

2.2.2 Ecotones and landscape edge effects

Studies investigating the effects of the landscape, particularly those related to forest edge (ecotonal effects), have increased over the past decade as researchers explore associations between forest fragmentation and dynamics of Lyme disease risk. Most of these studies have been performed in Europe or the United States, and all at scales that are useful for general modelling and regional public health awareness [58–66]. However, these studies at times present contrasting evidence for the associations between characteristics of the forest edge and environmental Lyme disease risk that make it difficult to translate research results into actionable guidance. In addition, none of the analyses to date have been conducted in regions experiencing blacklegged tick invasion and emergence, such as present in the Canadian context. These studies have been primarily focused on highly endemic areas where domestic or peri-urban exposures are the presumed event leading to *B. burgdorferi* transmission. In a Canadian municipality like Ottawa, Ontario, where blacklegged tick populations are newly and continually emerging, reports of peridomestic exposure are often considered abnormal and explanatory exposure locations are sought through a patient's recent travel history.

875 Understanding the role of the forest ecotone in Lyme disease risk is made more challenging by
876 the fact that hazard is often evaluated within forest patches of different sizes without accounting
877 for the interfacing land cover types that contribute to their fragmentation. The configuration and
878 environmental setting in which these edges exist requires thought; the favourability of conditions
879 in both the edge and the adjacent areas can differ between potential host preferences and habitat
880 suitability for ticks. Research focusing on edge habitat frequently assesses associations of Ixodid
881 tick density with the boundary between forest and open habitat (e.g., fields, parks), with mixed
882 results on whether abundance is greater in forest interiors [64] or in the shared ecotone
883 [62,63,65]. There is considerably less consensus on what effects fragmentation and edge habitat
884 have on the presence of *Peromyscus*-species mice [67–69]. Related characteristics of the forest
885 shape and community are hypothesized to drive observed edge effects. For example, Anderson et
886 al. [67] found that white-footed mice were present in greater densities in the edges of small forest
887 patches. Manson et al. [68] similarly found greater *P. leucopus* abundance in edge habitats, but
888 point to the specific edge contrasts (i.e., adjacency to old fields) and the territorial competition
889 with other small mammals – voles, in their study setting – as forces that push mice to inhabit
890 certain microhabitats. Nupp & Swihart [70] suggest that the overall ubiquity of white-footed
891 mice in tick-suitable microhabitats is due to their resilience to habitat fragmentation relative to
892 other small mammal species which favour woodland habitats under greater stress by
893 deforestation. Identifying effects of woodland ecotones on Lyme disease hazard is further
894 complicated by the relationship with tick reproductive hosts. White-tailed deer are known to
895 thrive and forage between open-canopy forests and edge habitats [71,72] but their movement can
896 effect whether male and female adult ticks that detach from deer drop off into suitable habitat.
897 Through a mathematical modelling approach, Li et al. [73] proposed that in the woodland-

grassland ecotonal context, grasslands might suppress tick abundance due to a higher probability of desiccation.

To date, few studies extend the examination of woodland ecotones to focus on the herbaceous or forested edge shared with residential properties [74,75]. Both Finch et al. [74] and Maupin et al. [75] evaluate this specific edge effect in residential areas from the perspective of individual properties, and only in long-endemic areas of the northeast United States. None yet evaluate the forest, ecotone and adjacent space contemporaneously. With plans in place to modify the landscape of Ottawa with new greenspaces and development opportunities [76–78], these changes should be made with a comprehension of how they may impact public health in the presence of emerging blacklegged tick populations.

2.2.3 Importance of considering scale in analytical associations

Studies that link environmental risk measures to Lyme disease incidence and hazard observe different effects at the regional, sub-regional, local, and property scales [79,80]. Assessed in areas with established Lyme disease endemicity, the strength of association between county-level DIN (density of infected nymphs) and Lyme disease incidence varies considerably between settings [81]. However, a risk of ecologic analyses is that at any scale, estimates presume that risk is homogeneous across the analysed spatial units.

In Canada, Lyme disease risk is geographically clustered with the majority of cases occurring in Ontario, Québec, and Nova Scotia [82]. At lower scales, more spatial clustering is evident, with

high correlation between incidence and submissions from passive tick surveillance reflecting the variability of blacklegged tick establishment across these different scales [83–85]. Some of this variability is due to regional differences in the rate of invasion of the blacklegged tick [82] but as smaller geographic units of analysis are considered, greater spatial heterogeneity indicates differences between the occurrence of peridomestic exposures and cases that result from tick encounters in nearby rural regions [84]. A similar need for focus on smaller units of analysis to best capture the convergence of hazard and vulnerability has been recognized even in endemic regions of the United States [79,86].

The question of scale in study designs is particularly relevant when considering associations with risk and strategies for targeted interventions [79,87]. In a comparison of multiple approaches to spatial data aggregation for incidence rate study designs, Jackson et al. [88] cautioned the need for careful boundary selection when assessing landscape design as a factor for zonal Lyme disease risk. Evaluations of enzootic hazard for Lyme disease support this, demonstrating scale-dependent differential effects of landscape characteristics on small mammal abundance, *B. burgdorferi* prevalence, and tick densities [65,89]. Recently, several studies of human Lyme disease incidence and reports of tick bites stress the importance of community context and local neighbourhoods as an appropriate level of analysis to identify locations for effective targeted mitigation strategies [87,90].

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Chapter 3

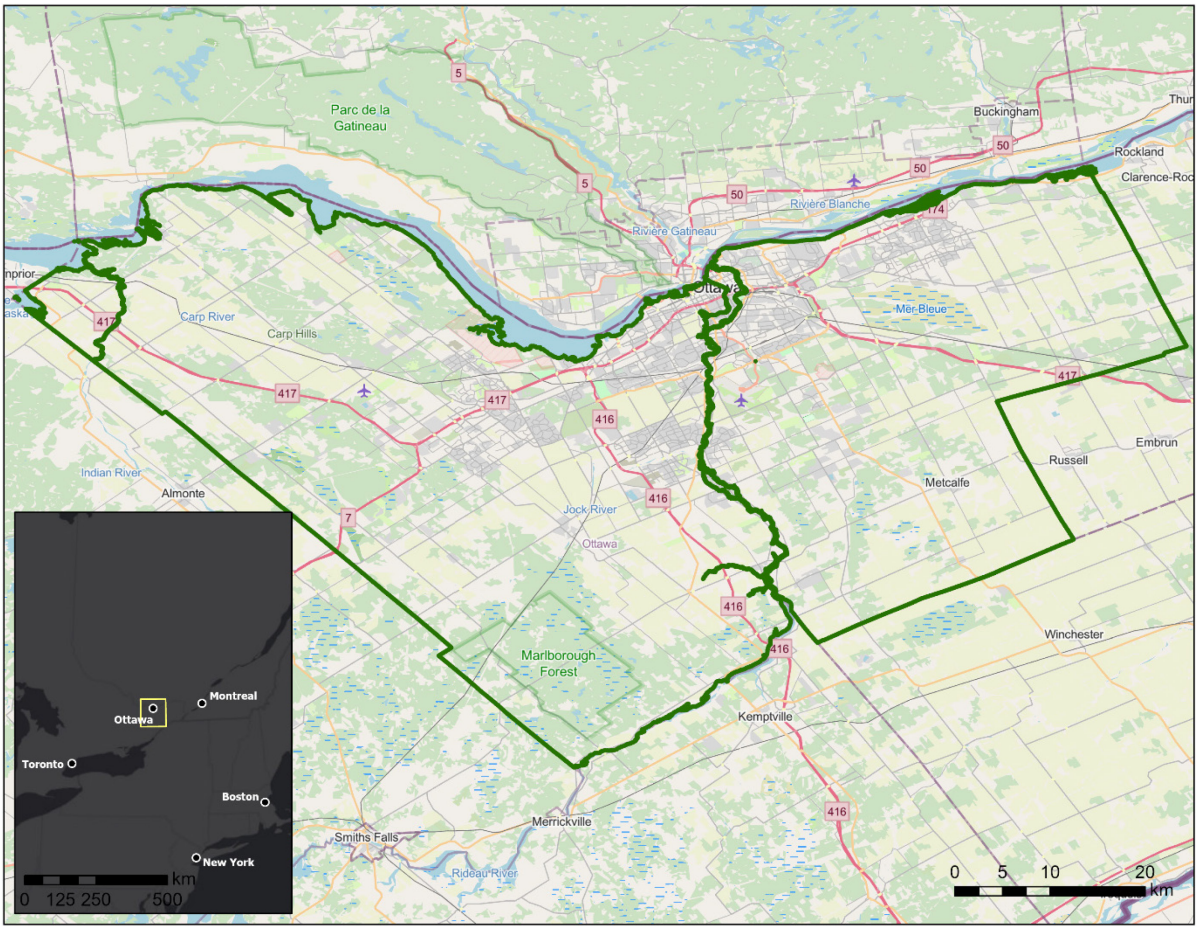
Methods

In this chapter, I describe the study area at the center of this research, as well as the origins and methods behind the various data sources. I also present some methods that were used in preliminary analysis to inform the core methods described in Chapters 4 through 6, including their results. While the specific methods employed to address the individual objectives of this thesis are described in their respective chapters, my aim is to invite the reader to become familiar with the methods used ahead of the main analyses that follow.

3.1 Study setting

The work in this thesis focuses on the municipal region of Ottawa, Ontario. The City of Ottawa was established as a risk area for Lyme disease in 2017 [1,2]. In 2018, Lyme disease incidence in Ottawa was nine cases per 100,000 population – lower than the three neighbouring provincial health units (Renfrew County and District; Leeds, Grenville & Lanark District; and Eastern Ontario) combined (30 per 100,000) [3]. By 2022, the difference in incidence between Ottawa and these neighbouring health units shrunk dramatically (20.6 per 100,000 compared to 36.8 per 100,000) [4]. Most recently, Ottawa Public Health reports that the Lyme disease incidence rate in 2023 rose to 27.7 per 100,000 population [3]. Both the provincial disease emergence patterns and the evidence of increasing environmental risk within the municipal region point to a rising local risk level [3,5–7].

Including the urban core, surrounding suburbs, and outlying rural communities, the City includes an area of almost 3,000 km^2 running east to west along the southern shore of the Ottawa River and extending 45 kilometres to the south (Figure 3.1). A unique feature of its landscape is the Greenbelt, comprised of sectors in the east and west halves of the city covering 20,000 hectares of protected trails, forests, farms and wetlands that blend the region's urban sprawl with natural areas [8]. To estimate the effect of forested area configuration on local risk, I focused the scale of my ecologic analysis in my first research objective on neighbourhoods defined by the Ottawa Neighbourhood Study (ONS) to represent physical and social similarities of communities [9]. These boundaries further served as a basis for the definition of urbanicity that I used to construct within-city regional strata to guide my second objective's KAP survey sampling design. Finally, prior tick surveillance activities informed the selection of sites in western Ottawa neighbourhoods with established high tick densities to identify associations with enzootic hazard present along the residential-woodland ecotone in my third objective [6,7].



1254

1255 **Figure 3.1** The City of Ottawa and its environs. The municipal boundary is indicated in dark green.
1256 Basemap is copyrighted by OpenStreetMap contributors, with data available under the Open Database
1257 License

1258

1259 **3.1.1 Defining urbanicity for population observations**

1260 To inform the stratified sampling design for my KAP survey, I defined urban, suburban, and
1261 rural regions of the city based on population density and other factors. This helped to ensure that
1262 the survey sample would capture population differences in tick exposure that are known to occur
1263 across rural and urban populations, as identified by Slatculescu et al. [10,11].

1264

Statistics Canada uses population density to define Canadian communities as either urban (greater than 400 people per square kilometre) or rural (less than 400) [12]. The definition of the 'suburbs' is more elusive and often relies on residents' perception of their surrounding community, making it the subject of extensive scholarly debate [13–15]. Using a definition of suburbanism informed by car commuting rates [16] applied to the natural neighbourhoods of the ONS [9], I selected neighbourhoods where car commuter rates imputed from Statistics Canada data by ONS were above the City of Ottawa average (i.e., 69%) or where ONS walkability measures suggested moderate car dependence (i.e., 20-50) for navigating the community. The resulting categorization of Ottawa neighbourhoods based on these definitions is depicted below (Figure 3.2). For the purposes of the KAP survey and analysis, I further sub-divided 'suburban' neighbourhoods into east, west, and south regions relative to the urban core and the Greenbelt area encompassing it. This division hypothesized that perceived levels of risk and behaviours among residents might reflect patterns observed in the ecological classifications of Lyme disease environmental risk among sites across the City of Ottawa identified by Burrows et al. [7], with more sites with established tick populations in the west relative to the east and south.

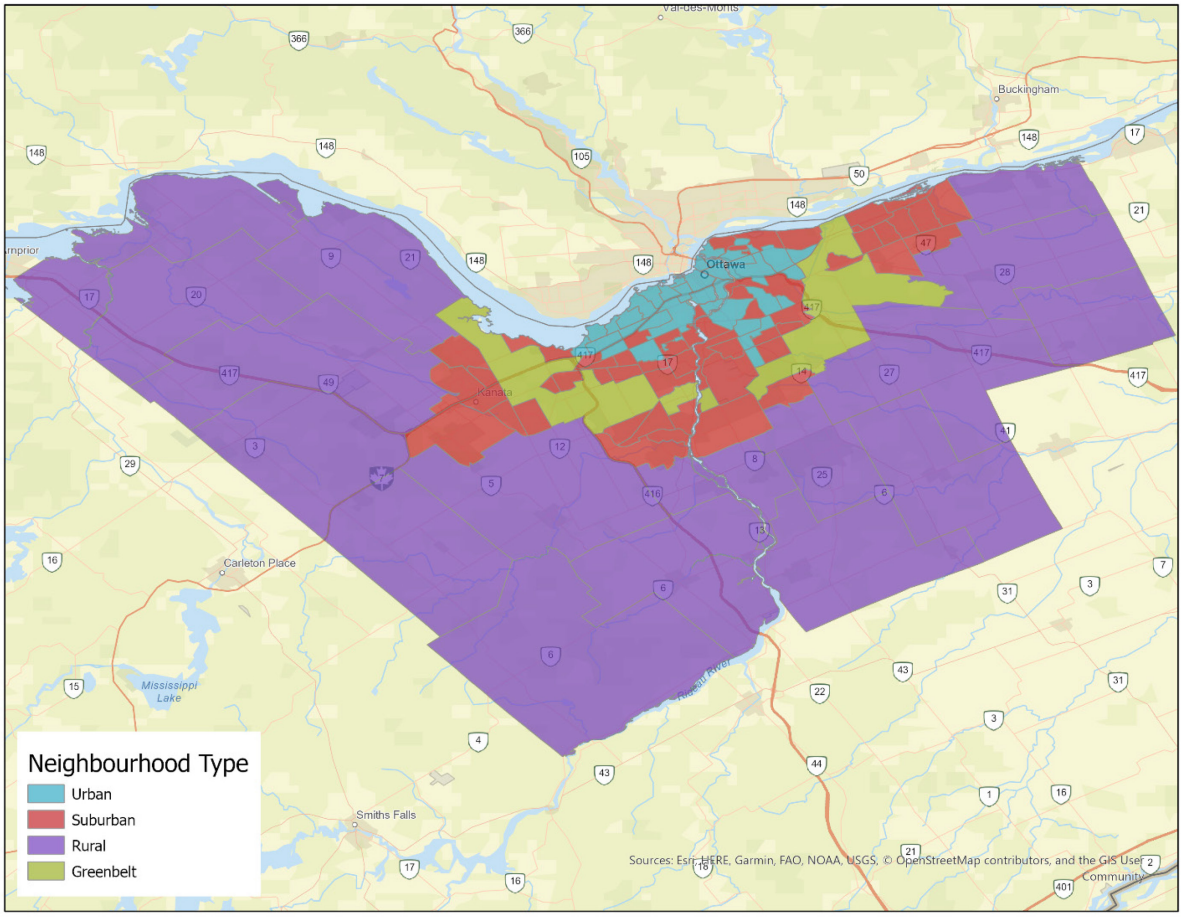


Figure 3.2 Ottawa neighbourhoods by urban, suburban, and rural classifications.

3.1.2 The modifiable areal unit problem (MAUP) and neighbourhoods as study units

In geography, the modifiable areal unit problem (MAUP) arises from the imposition of artificial geographic boundaries and the observation that different data sets with varying correlation structures are formed from changes to the boundary system used. This occurs due to two competing spatial processes intrinsic to boundary selection – zonal effects, where the location and orientation of boundary limits change the areal unit, and scale effects, which occur when the

spatial resolution, or size, or areal units is altered [17,18]. Thus, the MAUP emphasizes that there is an inherent bias in any choice of analytical spatial units.

For the analyses of my first objective, I chose neighbourhoods of the ONS for local area analysis because they are revised through consultation to define 'natural neighbourhoods' that represent community similarities. This approach to defining spatial zones accounts for social and physical elements and is philosophically aligned with the view of local geography under the One Health approach. The neighbourhoods also capture local areal units at a scale understudied in LD risk literature, which I highlighted in the previous chapter.

Two alternate spatial aggregations that illustrate the MAUP's zonal effect are dissemination areas and forward sortation areas. Both offer a similar spatial scale of analysis units yet are drawn with specific purposes based on human geography. Statistics Canada draws dissemination areas to balance statistical counting by uniform population sizes while following roads and other developed infrastructure. Forward sortation areas are administrative boundaries imposed by Canada Post for collecting postal codes and defining delivery zones. Aggregation and analysis with these areal definitions compared to the ONS boundaries are outside the scope of this thesis. Still, I describe them here to contrast how they consider the underlying population and highlight the suitability of ONS boundaries based on the community perspective.

3.2 Data Sources

I used a variety of data sources in the completion of this thesis, including: 1) surveillance and field observation data, 2) sociodemographic data, 3) remote sensing imagery, and 4) survey data.

3.2.1 Surveillance data

3.2.1.1 Human reportable disease data

Cases of Lyme disease are reportable data collected by public health units and shared with provincial and national surveillance systems to monitor regional and national patterns of incidence. The human case data used in this thesis were extracted from the integrated Public Health Information System (iPHIS) for the period between 2017 and 2020 and obtained through Ottawa Public Health under a data sharing agreement with the INSIGHT Research Lab. The data acquired included age, sex, date of disease onset, patient address, serological diagnostic testing results, and up to five reported locations of the suspected tick exposure, including recent travel history outside of Canada.

3.2.1.2 Active tick surveillance data

Members of the INSIGHT Research Lab performed tick drag sampling and small mammal trapping at sites within the Ottawa neighbourhoods of Kanata North, Stonehaven, Carp, and Stittsville between May and October of 2020 and 2021. These data contain information on the presence, abundance, instars, and *B. burgdorferi* infection prevalence of *I. scapularis* collected at sampling locations among 4 sites in each of residential, woodland, and residential-woodland interface ('interface') zones of these neighbourhoods. The number of ticks and infected ticks

were recorded and referenced to the GPS waypoint at which they were collected, from which further aggregation is described in more detail in the manuscript presented in Chapter 6. In June of both sampling years, field collectors recorded observations of the microhabitat from sampling locations along tick drag transects: percentage of canopy cover calculated using a spherical densiometer [19], litter layer depth in centimetres, percentage of soil moisture obtained from a soil moisture meter, and sampler observations of the dominant tree species and its relative abundance, understory density, site aspect, habitat type, and forest type.

The team compiled abundance and *B. burgdorferi* infection prevalence of *Peromyscus*-species mice at the zonal level of each neighbourhood. In both sampling years, 150 Sherman traps were set along both sides of trails used for tick drag sampling transects twice between June and August for two consecutive nights. Mice captured during each sampling night were briefly removed and inspected the next morning. Field collectors recorded sex, reproductive condition, length, weight, and quantities of any attached ticks. Animals were released after field collectors obtained one ear biopsy punch from each ear. Ethical approval for these activities was obtained from the University of Ottawa Animal Care Committee under permit ME-3079.

INSIGHT Research Lab staff also estimated deer foraging activity within zones of the four neighbourhoods from observations captured by trail cameras. One trail camera was installed in each zone at the end of June in both sampling years and moved 200 metres along the tick drag transect every two weeks until the middle of October. Images were filtered for only observations of white-tailed deer and the total number of events of unique deer observations were totaled.

Following established calculation methods for deer activity [20], zonal densities were calculated by dividing the number of events in the zone by the total number of camera-hours.

The relevant manuscript, presented in Chapter 6, describes in detail all field data collection methods conducted for this objective of my research.

3.2.2 Sociodemographic data

The Ottawa Neighbourhood Study (ONS) imputes sociodemographic characteristics from Statistics Canada surveys to generate neighbourhood-level estimates using boundaries of areas defined as 'natural neighbourhoods' by that project [9]. The geographic boundaries of neighbourhoods defined by the ONS project team were obtained for this thesis in the form of a GIS shapefile and linked to human reportable disease data based on patient address information to derive neighbourhood-level Lyme disease estimates. From the available neighbourhood-aggregated census statistics, I used the following:

- 2016 median household income (after tax), as a measure of neighbourhood socio-economic status (Objective 1);
- 2016 total population estimates, as count model offsets for population density differences (Objective 1) and a means of determining urbanicity status (Objective 2);
- 2016 estimates of the proportion of the population above age 15 who commute to their place of work by car, truck, or van, included in determination of urbanicity status (Objective 2); and

- August 2018 WalkScore data [21] obtained by ONS as a measure of how navigable nearby amenities are by foot, included in determination of urbanicity status (Objective 2).

3.2.3 Remote sensing imagery

To calculate measurements estimating the configuration and fragmentation of forested landscapes within ONS neighbourhoods, I acquired PlanetScope satellite imagery through the Education and Research Program of Planet Labs, Inc. [22]. By browsing the Planet Labs product catalog with a spatial filter applied for the municipal boundary of the City of Ottawa, I selected 38 4-band multispectral image tiles with 3.7-metre spatial resolution taken by PlanetScope Dove Classic satellites. All image tiles were obtained during August 2018 and processed by Planet Labs, Inc. to level 3B (orthorectified imagery with a cartographic projection) [23,24]. I manually selected satellite image tiles to ensure coverage of all ONS neighbourhood boundaries and the absence of cloud cover, allowing me to capture and derive the extent of vegetation present during the peak of the active tick season. This is described in detail in Chapter 4; briefly, I used Google Earth Engine to assemble a mosaic of the collected image tiles (panel A of Figure 3.3) and executed supervised classification of pixels in the mosaic using a random forest classifier to generate a land classification dataset (panel B of Figure 3.3).

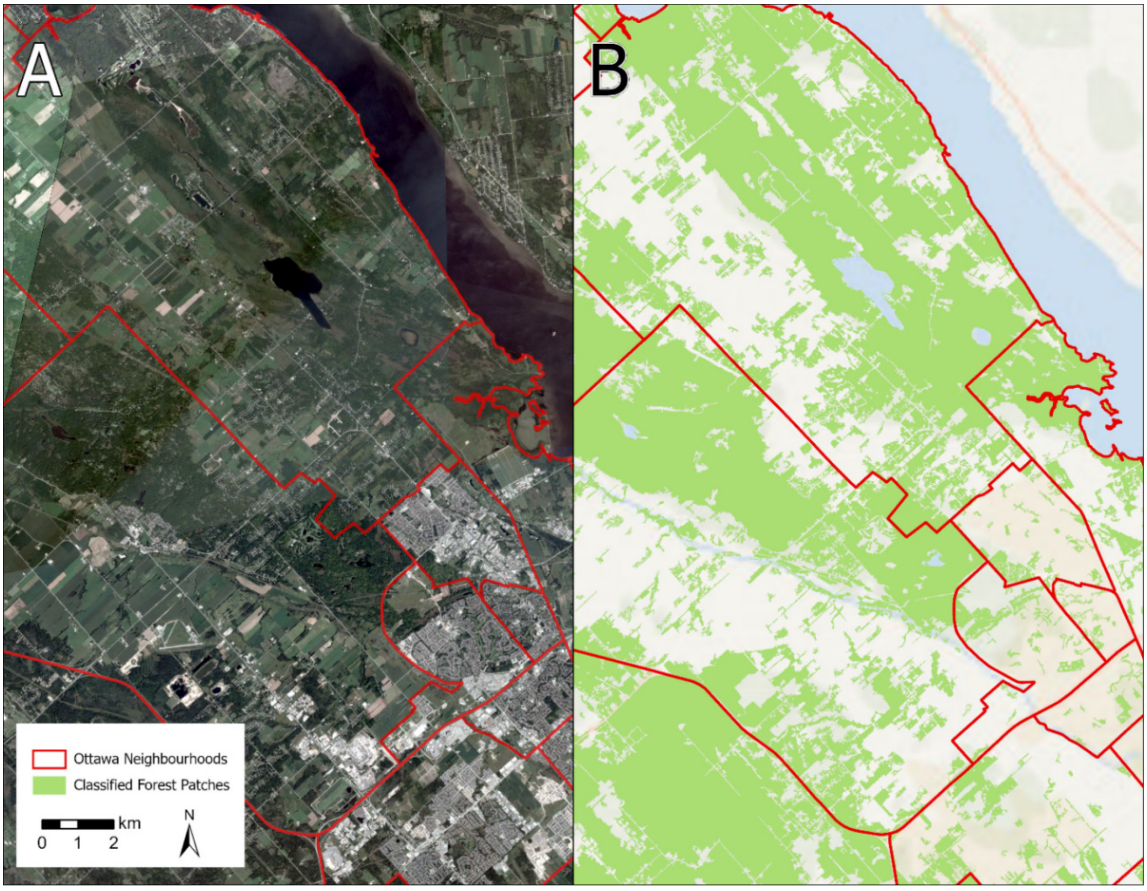


Figure 3.3 Example of original PlanetScope satellite images mosaic (A) and post-classification forested area polygons (B) in western Ottawa, Ontario.

3.2.4 Survey data

I used a cross-sectional survey instrument designed for this study to capture knowledge, attitudes, and practices (KAP) of Ottawa adults regarding Lyme disease, which was completed in November 2020 (Appendix B.2). The instrument was adapted from a combination of questions used to evaluate Lyme disease KAP of the Canadian population in a national study, as well as the Lyme disease questions from Ottawa Public Health Rapid Risk Factor Surveillance survey [25,26]. Along with sourcing sociodemographic characteristics of all respondents, the survey instrument included questions to evaluate Lyme disease knowledge (i.e., disease transmission,

protective measures, early symptoms, and treatment), personal perception of local risk, personal attitude towards specific prevention measures, personal adoption of preventive and protective behaviours, and past experience with tick bites and Lyme disease. I also asked respondents to identify up to three locations in "wooded areas or areas with tall grass and/or shrubs" that they visited frequently during the active tick season between May and October on an interactive web-enabled map. The survey was administered by Leger Opinion [27] to participants invited randomly from web panels using recruitment quotas to achieve a sample representative of the Canadian population and to satisfy balanced geographic representation across the city of Ottawa sampling strata (see section 3.1.1 above).

3.3 Exploratory analysis

3.3.1 Cluster analysis: Moran's I and Local Indicators of Spatial Autocorrelation (LISA)

A benefit of collecting human reportable disease data with geographic information related to incidence and suspected exposure is the ability to perform analyses that test for spatial patterns. However, in using these techniques, we must first accept that the spatial nature of the data violates the standard assumption of independence among observations required of statistical tests. This concept that "everything is related to everything else, but near things are more related than distant things" is considered the First Law of Geography, coined by geographer and early contributor to the field of geographic information systems (GIS), Waldo Tobler [28]. According to this fundamental principle, locations close to one another tend to exhibit similar characteristics and, as a function of distance, can be either positively or negatively correlated (spatial autocorrelation (SA)) [29]. The overall variation that arises between observations results from differences in scale [30]. Macro-scale (also, first-order) effects appear as global trends, occurring

as similar measurements of the same variable for all locations across an area of interest. Conversely, micro-scale (or, second-order) effects manifest as local dependence between observations, or spatial heterogeneity of measurements or occurrence [31].

GIS platforms allow us to quickly visualize and identify clear patterns in event data (e.g., human reportable disease cases) and classify those patterns as random, systematic (also, regular), or 'clustered.' Yet visible patterns may merely be a result of underlying autocorrelated processes which must be accounted for. In the case of Lyme disease incidence, cases can only occur when human-tick encounters lead to *B. burgdorferi* transmission. Thus, spatially clustered patterns of disease events largely exist due to any or a combination of global processes like the physical geography of the landscape, the distribution and abundance of blacklegged ticks in suitable habitats, or the distribution of the human population.

The human reportable disease data obtained from Ottawa Public Health included geographic data corresponding to patients' home address as well as the five most likely locations of exposure to an infected tick. I geocoded (assigned the appropriate latitude and longitude to case records to permit spatially-enabled analyses) all case records to the provided home postal code. With these locations, I manually reviewed each record and identified whether the first-named (most likely) exposure location was the same as the home address or a named location within the same ONS neighbourhood. With relatively small geographic boundaries available as a unit of analysis, I isolated on this 'local' classification of exposure to identify patterns in the emergence of risk unassociated with travel and aggregated local cases within ONS neighbourhood boundaries. Since the primary interest of my first objective was where local Lyme disease risk might be

greater across the Ottawa region, I used two methods to estimate second-order clustering effects: Local Indicators of Spatial Association (LISA) statistic for clusters and outliers of neighbourhood boundaries with high local Lyme disease incidence, and the Kulldorff Spatial Scan statistic to detect local clusters of cases as individual events.

3.3.1.1 LISA statistic

Moran's *I* is a coefficient of autocorrelation that quantifies how similar measurements of a variable (such as the frequency of an event occurring in an areal unit, e.g., Lyme disease incidence) are among adjacent areas [32]. This statistic is obtained by applying a spatial weights matrix to the deviance from the mean value for the whole study area, such that areas adjacent to one another are weighted more heavily than those that have a greater distance between them [32]:

$$I = \frac{n \sum_i^n \sum_j^n w_{ij} z_i z_j}{\left(\sum_i^n \sum_j^n w_{ij}\right) \sum_i^n {z_i}^2}$$

For my purposes, n represents the number of ONS neighbourhoods included in the Ottawa municipal region, z_i and z_j is the deviance between the mean number of local Lyme disease cases across all neighbourhoods and the observed number in neighbourhoods i and j, and w_{ij} is the spatial weight applied between those neighbourhoods. Conceived as a spatial statistic test for global phenomena, Moran's *I* can be interpreted as a statement on the presence of autocorrelation across the whole extent of the studied area.

The local indicators of spatial association (LISA) statistic breaks down the global estimate provided by Moran's *I* to parse the contribution of each study unit to autocorrelation over the whole area [33]. The LISA statistic for each study unit (i) is defined as:

$$I_i = z_i \sum_j w_{ij} z_j$$

where only the products of the deviance for observations at all other sites (j) and their row-standardized weight with i are summed. To achieve the spatial weighting across Ottawa's regional extent, I used an inverse distance conceptualization such that nearby neighbouring features were more influential on the calculation for each target feature than those on the other side of the city, standardized by dividing the weight by the sum of all adjacent neighbourhoods' weights. This application of standardization adjusts for bias that may be introduced by the aggregation of data into the imposed boundaries [34]. A False Discovery Rate (FDR) correction was also applied to account for multiple testing and lower the possibility of Type I errors [35]. The reduction in p-value thresholds leveraged to achieve this correction is determined by estimating the number of false positives expected for a 95% confidence interval with the given number of input features (here, 112 neighbourhoods), ranking all statistically significant p-values and removing a number of the weakest based on the estimated false positive rate [35].

I used the LISA statistic for the occurrence of local Lyme disease cases in Ottawa neighbourhood boundaries as a preliminary tool to assess the extent of local spatial autocorrelation and whether it necessitated spatial adjustment in count models. LISA statistics are accompanied by z-scores and p-values for each neighbourhood area; taken together, they indicate whether there is a statistically significant similarity (i.e., clusters) or dissimilarity (i.e., outliers) of each feature with those adjacent, beyond what might be expected if the counts occurred by complete spatial randomness (Figure 3.4) [34]. In the visual output given by the Local Moran's *I* tool of ArcGIS Pro 3.2, clusters are referred to as either 'High-High' or 'Low-Low', in that a neighbourhood

with a high value has neighbours with high values (pink areas in Figure 3.4) and those with low values are adjacent to others with low values (light blue areas in Figure 3.4). Similarly, outliers are termed 'High-Low' or 'Low-High' to designate that a neighbourhood with a high value is adjacent to or surrounded by areas with low observed values (red in Figure 3.4), or vice versa (blue in Figure 3.4).

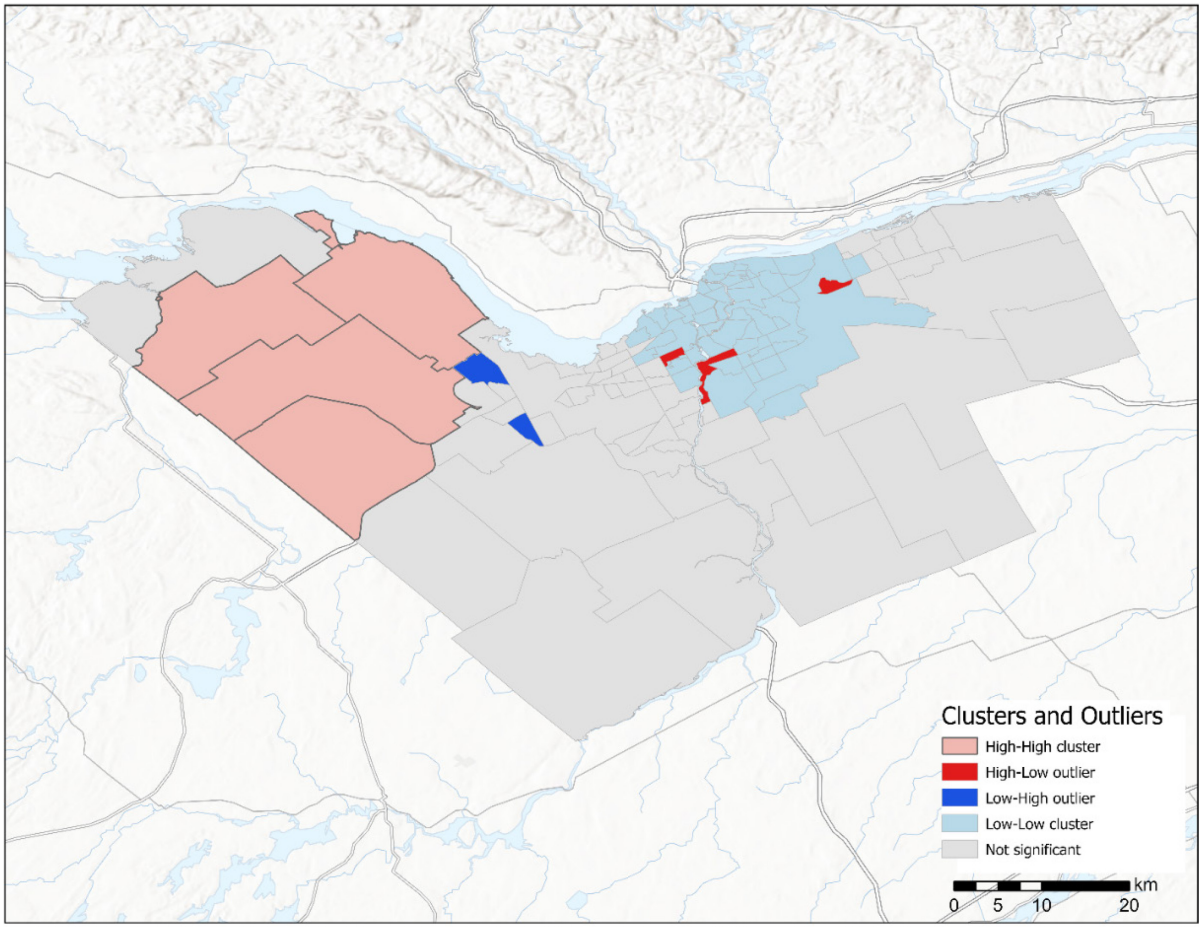


Figure 3.4 Clusters and outliers of Ottawa neighbourhoods with high and low local Lyme disease incidence, estimated by LISA statistics with an FDR correction applied.

3.3.1.2 Kulldorff's spatial scan statistic

Whether evaluated globally or locally, Moran's *I* is intended for use with continuous data. It is possible to use it for analysis of count data, as demonstrated above, though the estimated presence or absence of autocorrelation does not account for underlying variation in the population of the evaluated areas [31]. This can be handled by employing cluster detection methods for point data which seek to identify geographically grouped events (cases) such that they are unlikely to be concentrated to the area in which they occur by chance [36]. One method to achieve this is the spatial scan statistic developed by Kulldorff [37].

In this technique, for every case in the dataset a series of circles ("scanning windows") centered on that point is tested until the circle includes a pre-determined proportion of the underlying population at risk, at which time the number of cases that fall within the scanning window around the focal case is recorded [38]. With the final size of the scanning window identified, the maximum likelihood for that circle is calculated with the alternative hypothesis that there is an elevated risk of disease inside the scanning window relative to outside it [39]. In SaTScan, the software in which Kulldorff implemented his methodology, the scan statistic (*S*) is calculated from the maximum likelihood ratio for all possible scanning windows in a Poisson model [39,40]:

$$S = \max_{Z} \left\{ \frac{n_Z}{\mu(Z)} \right\}^{n_Z} \left\{ \frac{N - n_Z}{N - \mu(Z)} \right\}^{N - n_Z}$$

where n_Z is the number of cases which fall within scanning window Z, N is the total number of cases that occurred in the study area and over the period of interest, and $\mu(Z)$ is the expected

number of cases in the scanning window under the null hypothesis (i.e., that risk is equal inside and outside the window).

Under the Poisson distribution, the scanning software determines the expected number of cases ($\mu(Z)$) using the proportion of population provided in an independent population file. In my application of the technique, I supplied a population file with coordinates of Statistics Canada dissemination areas (DA) with 2016 populations by age and sex [41] and specified that the maximum spatial cluster size should include 20% of the underlying population at risk. The output from the SaTScan tool allows for visualization of significant clusters of cases in GIS software, which I demonstrate in Figure 3.5. With these parameters, the clusters reflect the high and low incidence areas reported by the LISA statistic (Figure 3.4) while also identifying localized clusters of local Lyme disease cases – a large circular area slightly less than 25 kilometres in diameter with a relative risk of 23.1 for the area inside it compared to outside, centered on the western neighbourhoods of Carp and Dunrobin, and a smaller circular area just under 7 kilometres wide where residents in Bridlewood, Bell's Corners, and parts of the western Greenbelt were at 11.30 times greater risk of Lyme disease than other areas in the city.

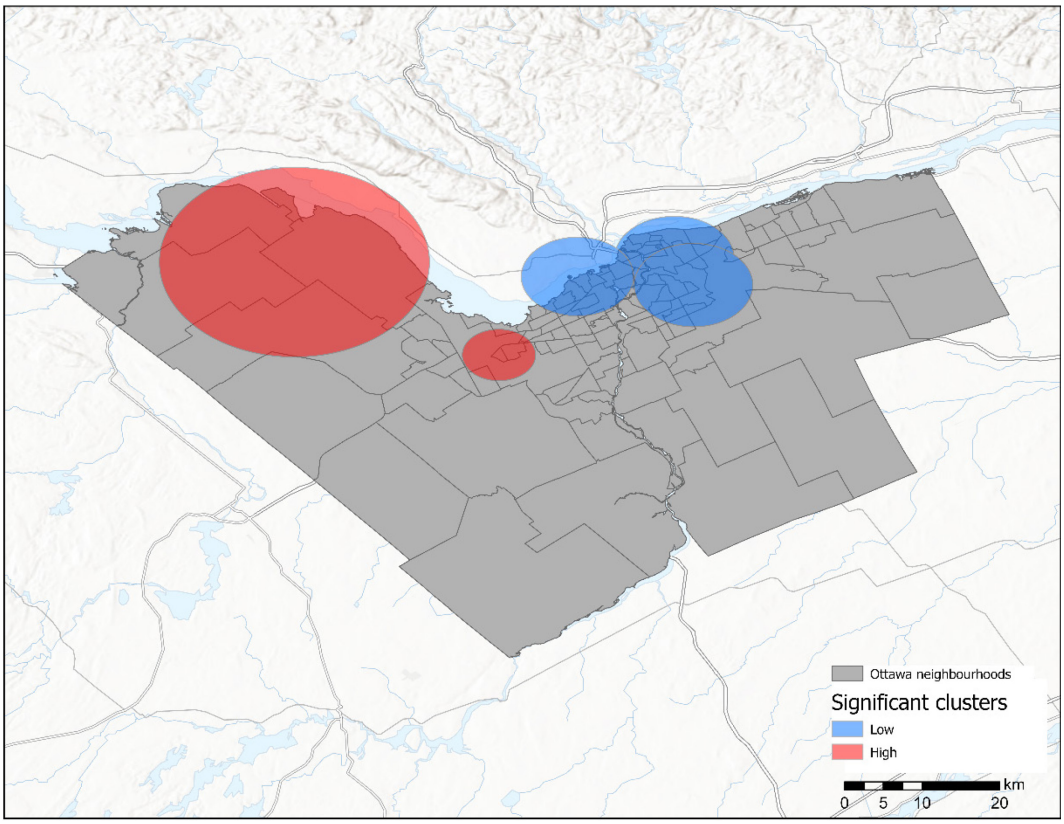


Figure 3.5 Significant clusters of Lyme disease case locations, estimated by the Kulldorff spatial scan statistic

The results from this cluster detection technique, taken with the areas identified by the LISA statistic, provided evidence for the necessity of a method to deal with spatial autocorrelation in further evaluation of local incidence of Lyme disease in the neighbourhoods of Ottawa, which I describe further in section 3.4.1.

3.4 Modelling counts

The outcomes in my first and third objectives both deal with count data – non-negative observations about the number of events (cases of Lyme disease) or individuals (collected ticks) enumerated in a defined area (neighbourhoods and sampling quadrats, respectively). The

modelled outcomes are always limited by a lower boundary of zero and tend to be right-skewed – a high probability of few observations and lower for observations in greater numbers. While the Poisson probability distribution is fundamental to describing relationships with count outcomes, it assumes that the mean and variance of the outcome are equal (equidispersion). Therefore, when the mean is greater, and larger counts of individuals or events are observed more often, the variability of possible values is also greater. However, observations of events that are rare (i.e., cases of Lyme disease) or difficult to detect (i.e., questing ticks) may violate this assumption. In these cases, the variability in the possible number of observations is much larger than its mean, a condition termed overdispersion [42]. Departures from equidispersion can be tested by calculating an index of dispersion, defined as the ratio of the response variable's variance to its mean. When this test statistic is approximately 1.0, a Poisson distribution can be adopted in generalized linear models (GLMs) to represent the frequency of observations in the data; when the dispersion statistic exceeds 1.0, a negative binomial (NB) distribution is appropriate to adjust for the presence of overdispersion in the data. In this case, to ensure the GLM is constructed on a probability distribution that best represents the data being modelled, the negative binomial includes a dispersion parameter to adjust for a wider distribution of potential counts than is possible in the Poisson model [43].

Importantly, basic count models assume that the number of observations in the data emerges from an equal area or number of individuals. However, when the counts arise from a background population or environment that varies in size, the natural log of the volume unit (i.e., area, population) must be included among the modelling parameters as an offset term [42]. In my first objective, GLMs of local Lyme disease incidence occurring in Ottawa neighbourhoods required

an offset for the total neighbourhood population. With this inclusion, the result of the estimating algorithm is the local Lyme disease incidence rate ratio for neighbourhoods over the study period (2017-2020). By contrast, my analysis of the residential-woodland habitat gradient performed to meet my third objective did not require an offset term as estimations of the density of *I. scapularis* ticks were calculated for study units of equal area.

All GLMs of count data aim to estimate the rate at which a given number of observations occur – for example, how often X cases of Lyme disease are diagnosed in a given area over the designated period of time. Like the Poisson distribution, the general shape of the negative binomial can be approximated by a log-linear equation, with the inclusion of parameters adjusting for overdispersion and population offsets. That is, a logarithmic transformation of the predicted rate can be estimated by the following linear function:

$$\log(Y_i) = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k + \log(t_i)$$

where Y is the number of observations of the individual or phenomenon studied in area *i*, β_0 is the intercept or the log-transformed number of events in the absence of explanatory variables, β_k is the effect or slope of each predictor x_k describing the change in the expected log-transformed number of events for one unit differences in the value of x_k, and *t* is a constant representing the size of the underlying population at risk (alternatively, the variable area or period of time evaluated) at location *i*. The models fit in my third objective also use random intercepts for the four study neighbourhoods, with fixed effects to adjust for between-neighbourhood heterogeneity in characteristics associated with the presence and survival of reproducing tick populations. I determined that it was unnecessary to further account for between-neighbourhood differences as this study was observational (as opposed to experimental), using observations recorded once per

study year for the fixed covariates rather than as repeated measurements at each tick drag occurrence.

3.4.1 Spatial filtering

The negative binomial GLMs fit for local case data in my first objective included an offset term for the 2016 total population. However, the preliminary analyses detailed in section 3.3 highlighted the need to account for spatial autocorrelation of local Lyme disease incidence that exists beyond adjustment for the underlying population at risk in these neighbourhoods. There are a variety of methods to account for spatial autocorrelation in models representing spatial data [44]. These include adjustment via inclusion of spatial covariates (i.e., latitude and longitude coordinates of study units), spatial eigenvector filtering, generalized least squares, autoregressive models, and spatial generalized estimating equations [44]. The analysis I present in Chapter 4 involved several sources of data aggregated within neighbourhood boundaries (i.e., forest configuration measurements, median household income) each entangled with the human population and latent tick hazard distributed across the whole landscape. Griffith [45] proposes spatial eigenvector filtering as an approach to describe complex geographic patterns, based on the premise that the spatial arrangement of the data can be included as explanatory factors.

To apply spatial filtering, I constructed a spatial connectivity matrix to represent the adjacency of study units to one another and applied geographic weighting based on the distance between each unit across the matrix. A global Moran's *I* estimate, which I calculated for the entire study area and applying the same spatial connectivity matrix, produced eigenvectors that represent a decomposition of the Moran's *I* statistic [46]. During analysis, I plotted the eigenvectors along

with the covariates of interest to capture the particular spatial pattern contributing to collinearity of the variables that arises from the complex relationships inferred by their spatial autocorrelation and filter it from coefficient estimates and residuals [45].

3.5 Survey methodology

Numerous studies of Lyme disease knowledge, perception, risks and practices have administered surveys via the Internet for both national and regional scales [25,47–51]. One of these, a study of Lyme disease preventive behaviour adoption in Québec, reported their web-survey sample was no less representative of the target population than a telephone survey [51]. The questionnaire developed for my cross-sectional survey of Ottawa adults (Appendix B.2) was administered through the web panels of the Canadian survey and analytics company Leger [27] and their partners between November 5 to 25, 2020. The specific format of the questions is described in greater length in Chapter 5.

3.5.1 Sample size calculation

The survey sample size for this study was determined using the formula for estimating a population proportion provided by D'Agostino et al. [52]:

$$n = p(1-p)\left(\frac{Z_{1-(\alpha/2)}}{E}\right)^2$$

where $Z_{1-(\alpha/2)}$ represents the specified confidence level, p is expected population proportion, and E is the acceptable margin of error. For this survey, we aimed to determine whether the proportion of Ottawa respondents in each pre-defined city region with a high level of Lyme disease knowledge was significantly different from 60%, a proportion slightly greater than was

reported for Ontario in a national survey [48]. To make this inference at a 95% confidence level within a 5% margin of error, we required 370 (rounded up from 368.79) responses per city region stratum. Leger applied recruitment quotas through the web panels to achieve a sample representative of the Canadian population and ensure a balanced geographic representation based on the sample size required from each city region (urban, rural, suburban east, suburban west, suburban south).

3.5.2 Limitations of the KAP survey approach

A criticism of KAP surveys is that the cross-sectional nature of these studies fails to capture the social context, motivations, and personal drivers (e.g., perception, self-efficacy, and societal norms) that shape behaviours [53]. As such, this survey methodology cannot help us understand the rationale behind individuals' behavioural choices. It provides a 'snapshot' of the population-level vulnerability for the surveyed population, aligning the results with the scale of geography at which I evaluate LD risk and hazard in my first and third objectives.

While it is important to improve our understanding of the motivations behind use, non-use, or combinations of protective behaviours in LD research, these personal choices are best studied by qualitative or mixed-methods studies which could require significant resources and time to obtain a sample size that would characterize these aspects of vulnerability at the neighbourhood level and across the Ottawa municipal region. It is also important to note that this study was conducted during the COVID-19 pandemic, during which engaging participants in interviews or focus groups could have been more challenging.

3.6 Chapter Summary

In this chapter, I described the study setting and spatial scale that my analyses focused on. I also briefly summarized the data used for the studies described in detail in the following pages, as well as some of the exploratory analyses that prefaced the main statistical approaches undertaken to address the main thesis objectives. Finally, I presented a general overview of the field research, statistical, and analytic approaches that are central to the next three chapters.

3.7 Chapter References

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Chapter 4

Local Lyme disease risk and characteristics of neighbourhood landscapes

4.1 Article preface

This chapter explains how I examined the landscape-scale association between measurements of neighbourhood forest configuration and Lyme disease acquired through residential exposures. I used case data provided by Ottawa Public Health and geocoded cases to their home postal code. I included cases for analysis if the first exposure location they provided to public health officials matched their home address and aggregated the number of cases to the appropriate Ottawa Neighbourhood Study boundary. I also obtained and processed satellite imagery from Planet Labs Inc. to derive high-resolution measurements of forest land cover attributed within Ottawa neighbourhoods. I examined five hypothesized interactions of neighbourhood characteristics to explore associations between the neighbourhood landscape structure and local Lyme disease risk.

4.1.1 Author contributions

I designed the research question with guidance from my research supervisor, Dr. Manisha Kulkarni. I developed the methodology and performed all analyses, including data cleaning, processing, code development, and statistical modelling. Amber Hoi assisted in model selection and validation of the spatial filtering method used in model adjustment. I received valuable guidance on the methodology from Drs. Manisha Kulkarni, Nicholas Ogden, Justine Blanford, Tim Ramsay, Anders Knudby, and Michael Sawada.

4.1.2 Ethics approval

Ethical approval for this study was obtained from the University of Ottawa Health Sciences and Science Research Ethics Board (file number H06-16-22).

4.1.3 Article citation

Logan JJ, Hoi AG, Sawada M, Knudby A, Ramsay T, Blanford JI, et al. (2023) Risk factors for Lyme disease resulting from residential exposure amidst emerging *Ixodes scapularis* populations: A neighbourhood-level analysis of Ottawa, Ontario. PLoS ONE 18(8): e0290463.

4.2 Article Content

4.2.1 Title

Risk factors for Lyme disease resulting from residential exposure amidst emerging *Ixodes scapularis* populations: a neighbourhood-level analysis of Ottawa, Ontario

4.2.2 Authors

James J. Logan
School of Epidemiology and Public Health, University of Ottawa, Ottawa, Canada

Amber Gigi Hoi
School of Epidemiology and Public Health, University of Ottawa, Ottawa, Canada

Michael Sawada
Department of Geography, Environment and Geomatics, University of Ottawa, Ottawa, Canada

Laboratory for Applied Geomatics and GIS Science, University of Ottawa, Ottawa, Canada

Anders Knudby
Department of Geography, Environment and Geomatics, University of Ottawa, Ottawa, Canada

Tim Ramsay
School of Epidemiology and Public Health, University of Ottawa, Ottawa, Canada
Ottawa Hospital Research Institute, University of Ottawa, Ottawa, Canada

Justine I. Blanford
Department of Earth Observation Science, Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, Netherlands

Nicholas H. Ogden
Public Health Risk Sciences Division, National Microbiology Laboratory, Public Health Agency of Canada, Saint-Hyacinthe, Canada

Manisha A. Kulkarni
School of Epidemiology and Public Health, University of Ottawa, Ottawa, Canada

4.2.3 Abstract

Lyme disease is an emerging health threat in Canada due to the continued northward expansion of the main tick vector, *Ixodes scapularis*. It is of particular concern to populations living in expanding peri-urban areas where residential development and municipal climate change response impact neighbourhood structure and composition. The objective of this study was to estimate associations of socio-ecological characteristics with residential Lyme disease risk at the neighbourhood scale. We used Lyme disease case data for 2017-2020 reported for Ottawa, Ontario to determine where patients' residential property, or elsewhere within their neighbourhood, was the suspected site of tick exposure. Cases meeting this exposure definition

(n=118) were aggregated and linked to neighbourhood boundaries. We calculated landscape characteristics from composited and classified August 2018 PlanetScope satellite imagery. Negative binomial generalized linear models guided by *a priori* hypothesized relationships explored the association between hypothesized interactions of landscape structure and the outcome. Increases in median household income, the number of forest patches, the proportion of forested area, forest edge density, and mean forest patch size were associated with higher residential Lyme disease incidence at the neighbourhood scale, while increases in forest shape complexity and average distance to forest edge were associated with reduced incidence ($P<0.001$). Among Ottawa neighbourhoods, the combined effect of forest shape complexity and average forest patch size was associated with higher residential Lyme disease incidence ($P<0.001$). These findings suggest that Lyme disease risk in residential settings is associated with urban design elements. This is particularly relevant in urban centres where local ecological changes may impact the presence of emerging tick populations and how residents interact with tick habitat. Further research into the mechanistic underpinnings of these associations would be an asset to both urban development planning and public health management.

4.2.4 Introduction

Climate change is having diverse and profound impacts on human health. Extreme heat and erratic precipitation patterns, resulting in issues of food security and increased infectious disease burden are all growing concerns [1]. Governments across all levels recognize the need to respond to these challenges with mitigation and adaptation strategies [2,3]. In particular, the decisions made by municipal governments can directly address the impacts of climate change at a much

more rapid pace than other levels of government [4]. Actions that develop green infrastructure, however, must balance the need to accommodate population growth, through urban expansion by cities of all sizes, and to minimize the resulting impacts on local ecosystems [5,6]. Intertwined with climate trends and local land use changes are effects on the distribution, life cycles, and transmission dynamics of disease vectors and pathogens. Overall, changes in climate have resulted in an expanded range for many disease vectors in North America and Europe, such as mosquitoes and ticks [7,8]. At the municipal level, community needs and climate change response strategies – such as urban greening to mitigate urban heat island effects – contribute to changes in the landscape. Such changes often impact local ecosystems in myriad ways. However, efforts to quantify the nature of landscape effects has focused on larger areal units with little analysis of more local vector-borne disease risk [9,10].

Local transmission of vector-borne diseases is an issue of increasing importance in Canada, attributed to the widening geographic range of disease vectors made possible by the expansion of suitable climatic conditions and habitat [7,11]. Lyme disease is one of the most significant vector-borne diseases in Canada. *Ixodes scapularis* (blacklegged ticks) transmits *Borrelia burgdorferi* (the bacterial agent of Lyme disease in humans) in eastern North America. Emerging populations of ticks result from the changing migratory patterns of passerine bird species that carry them from regions with established populations (e.g., eastern United States and southern regions of Canada). Once present, ticks may become established under new climatic conditions that allow them to persist through once-inhospitable winters [8]. In 2009, the government of Canada identified Lyme disease as a priority for surveillance, prompting its designation as a nationally notifiable disease [12] and establishing it as an emerging infectious disease of public

health concern [13]. In Canada, the incidence of Lyme disease cases has increased from 338 in 2012 to 2,168 in 2022 [14] with cases reported over an expanding geographic range. Active surveillance for questing ticks in the municipal region of Ottawa, Ontario demonstrates that suburban and rural areas of the city exhibit increasingly stable entomological hazard, both in presence of *I. scapularis* ticks and *B. burgdorferi* infection prevalence among collected ticks [15–17].

In areas where endemicity of tick-borne pathogens, particularly *B. burgdorferi*, is long-established, the domestic risk – where exposure to ticks occurs on a residential property – has earned public attention [18,19]. In the Northeast United States, there is evidence that knowledge of Lyme disease risk has influenced human behaviour, particularly where people choose to live [20]. While awareness of Lyme disease varies across regions of Canada, less than half of Canadians with awareness of Lyme disease risk personally adopt preventive behaviours [21,22]. Yet, local attention is often required to mitigate environmental Lyme disease risk arising from regional invasions of ticks and the emergence of tick-borne pathogens.

While recent research in Canada has focused on modelling the expected regional presence of the blacklegged tick to inform public health programs [23,24], there are few evaluations of local impacts where changing municipal landscapes coincide with emergent tick invasions. With few exceptions [25–27], previous studies in eastern North America have focused on Lyme disease risk factors at the regional, state, and county level [28]. Brownstein *et al.* [25] related landscape indices – mean forest patch size and mean patch isolation – to increases in town-level tick density and tick infection prevalence but lower Lyme disease incidence over a twelve-year period

in the state of Connecticut. Jackson *et al*. [26] and Seukep *et al.* [27] each examined the relationship between indices of edge contrast – where different land cover types shared adjacency with forested areas – to five-year incidence rates of Lyme disease at a scale comparable to census tracts in the states of Maryland and Virginia, respectively. Both studies found a positive correlation of greater herbaceous-forested landcover edge contrasts with local incidence rates. While the authors of all three studies illuminate the above associations between the interspersion of forests and other land types with peridomestic Lyme disease risk, they do not explore the influence that local ecotones, or how forested land cover is configured and integrated, have within cities. Furthermore, they also assume that all reported cases result from tick bite exposures that occur within the towns or census tracts studied. To address this gap, we simultaneously examined the contributions of neighbourhood-level socio-economic conditions and forested landscape composition to residential Lyme disease risk in a large Canadian population centre. Such research is fundamental for informing landscape management and planning as municipalities grow and adapt.

4.2.5 Methods

4.2.5.1 Study area

The City of Ottawa, Ontario extends 45 kilometres south from the Ottawa River and covers nearly 3,000 km^2 east to west along its shared border with the province of Quebec (Figure 4.1). Together with Gatineau (the Quebec side of the Ottawa River), it comprises the fourth largest metropolitan area in Canada with nearly 1.4 million people. The City of Ottawa itself contains just over 1 million people inhabiting 112 neighbourhoods within the city limits, as defined by the

Ottawa Neighbourhood Study (ONS) [29]. Within these limits, the most densely populated urban areas are partitioned from suburban and rural communities by a protected stretch of trails, forests, farms, and wetlands known as the Greenbelt [30]. This balance of developed and natural environments results in a landscape where residents live within proximity to, and interact with, various habitat types with high biodiversity [6]. We chose neighbourhoods identified by the ONS as the study area unit because they represent 'natural neighbourhoods' [31] that have been honed via participatory mapping and community consultation and thus reflect physical and social similarities that affect area residents. Statistical analysis was restricted to 108 neighbourhoods, excluding neighbourhoods with very low recorded population figures (i.e., two cemeteries, one university campus) as well as the expansive Greenbelt, which is aggregated into one neighbourhood in the ONS.

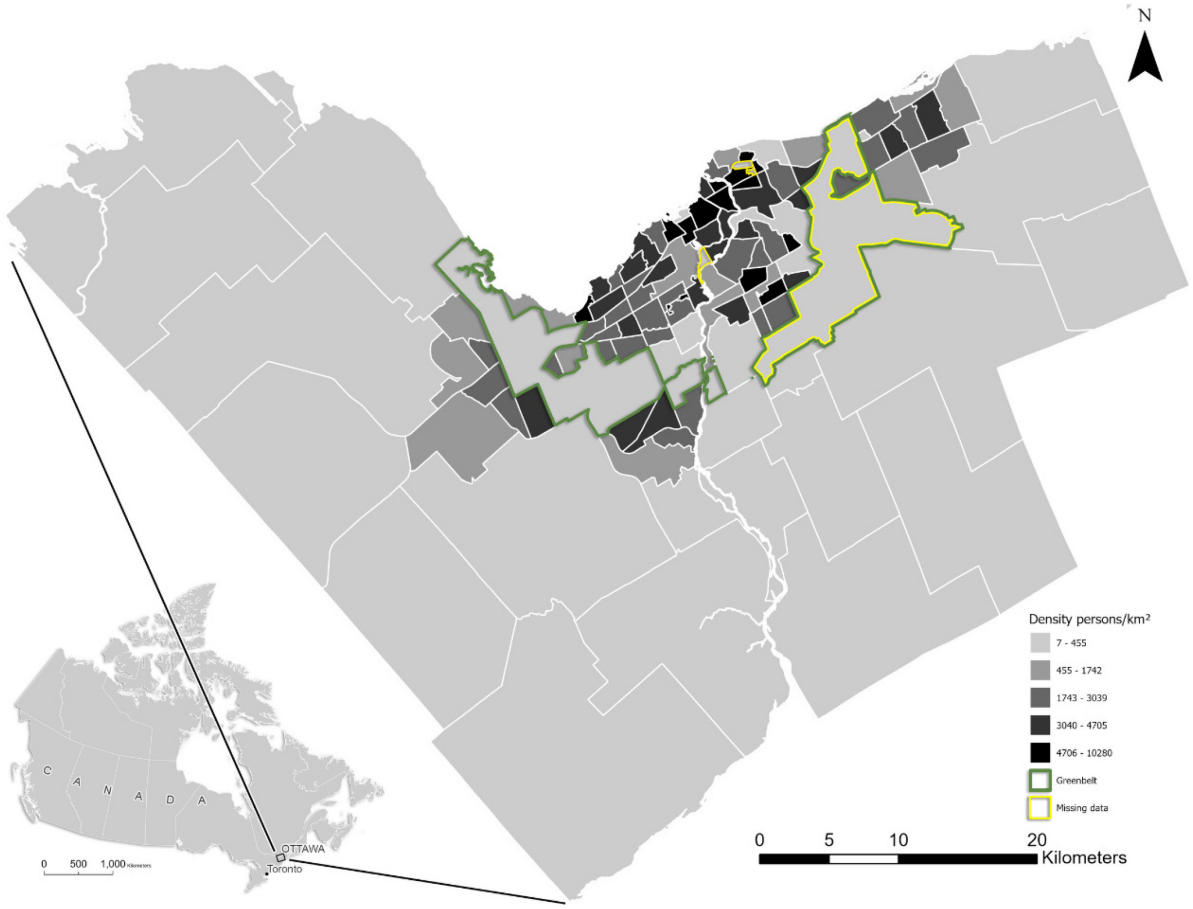


Figure 4.1 Neighbourhood boundaries (n=112) with population densities for Ottawa, Ontario. Locations of the Greenbelt and neighbourhoods with no population figures are highlighted.

4.2.5.2 Ethical approval

We obtained ethical approval for this study from the University of Ottawa Health Sciences and Science Research Ethics Board (file number H06-16-22).

4.2.5.3 Dependent variable

The dependent variable in this study is the number of Lyme disease cases in each neighbourhood reported as exposure on an individual's residential property or nearby neighbourhood locations,

adjusted for the total neighbourhood population. We used reported Lyme disease case data between 2017-2020 that were extracted by Ottawa Public Health from the integrated Public Health Information System (iPHIS) based on the Lyme disease case definition [32]. Case records included the age, sex, date of disease onset, address, and up to five reported locations for likely tick exposure, including recent travel history. We mapped cases to residential location by their 6-digit postal code and identified the neighbourhood the case resided in. The first-named exposure location was taken as the most likely and each case was designated as either 'Residential', where the provided exposure location matched the patient's home address exactly or elsewhere within the neighbourhood, or 'Non-residential', where the exposure occurred at a location outside the patient's home neighbourhood. We then aggregated the count of residential cases occurring within home neighbourhoods across all four years of the study.

4.2.5.4 Independent variables

We evaluated associations between neighbourhood-level socio-economic and landscape characteristics and the incidence of residential Lyme disease cases. Data sources and methods used to derive each independent variable are described below. The rationale for the use of each measurement in estimating a relationship with the outcome is detailed in Table 4.1. In all statistical analyses, these independent variables were treated as continuous values and standardized (mean-centred and scaled to units of one standard deviation).

2048 **Table 4.1** Rationale and descriptive statistics of variables used to characterize Ottawa neighbourhoods, stratified by presence and absence of
2049 residential Lyme disease cases.

			All Neighbourhoods (n = 108)			1+ cases (n = 46)			0 cases (n = 62)		
Variable	Rationale	Units	Mean	Median	Standard Deviation (SD)	Mean	Median	SD	Mean	Median	SD
Proportion forest landcover	High proportions of forested area increase the potential for high abundance of vectors and competent reservoirs.	%	17.41	11.39	18.55	21.26	14.26	20.98	14.62	8.99	16.16
Number of forest patches	Higher numbers of independent forest patches may indicate that more residential properties border forest fragments where small mammal populations can occur in greater abundance [33].	#	34.53	6	64.31	55.47	8.00	81.26	19.34	5.00	43.19
Forest edge-to-area ratio	Forest with more complex geometric shapes (longer perimeter when patches have equal size) allow more residential properties adjacency to forest edge.	km / km^2	739.35	647.94	390.27	680.2	614.5	369.87	782.3	710.6	401.92
Mean address-edge distance	Neighbourhoods with a shorter distance between addresses and forest edge may indicate more properties border forests, with greater likelihood of tick encounters.	metres	259.71	226.59	174.46	235.87	189.73	181.99	277.02	235.99	168.15
Edge density	Greater amount of forest edge per total neighbourhood area translates to higher amount	km / km^2	8.70	7.42	6.73	9.24	10.12	5.81	8.31	6.34	7.34

	of other land types bordered by forest, increasing overall opportunities for tick encounters.										
Mean forest patch size	Greater average forest patch size indicates larger forest patches more capable of sustaining a disease transmission cycle with larger small mammal (e.g., white-footed mice) population sizes.	km^2	2.57	0.13	6.76	3.87	0.41	7.15	1.62	0.08	6.35
Median household income (after tax)	Higher average income is associated with single-detached residential property types [34]. Larger lot sizes may more often border tracts of woodlands and show association with high Lyme disease risk.	$000	$75.74	$76.01	$24.28	$81.10	$82.25	$19.69	$71.84	$73.65	$26.61

4.2.5.4.1 Ottawa Neighbourhood Study data

The Ottawa Neighbourhood Study (ONS) aggregates and calculates indicators representative of social determinants of health from custom-tabulated Statistics Canada surveys and municipal datasets for all Ottawa neighbourhoods, as explained in detail elsewhere [35]. We selected 2016 median household income (after tax) as a measure of neighbourhood socio-economic status and general measure of inequality to examine its association with incidence of residential Lyme disease [36]. Use of this income variable is consistent with prior studies of Lyme disease risk factors across various geographic scales [26,27,37,38]. The ONS also provided population estimates by neighbourhood generated from the 2016 Statistics Canada census [35].

4.2.5.4.2 PlanetScope imagery forest measurements

We evaluated the amount of forested area within each neighbourhood using six measurements derived from PlanetScope satellite imagery. To calculate these variables, we selected 38 4-band multispectral images with 3.7-metre spatial resolution taken by PlanetScope Dove Classic satellites during August 2018 and processed to level 3B (orthorectified imagery with a cartographic projection) to capture the extent of vegetation during the summer season [39,40]. We used images from the final week of this month, selected manually to minimize cloud cover, ensuring all land within the municipal boundaries of Ottawa could be classified. Using Google Earth Engine (GEE) [41], we generated a composite image (mosaic) from the collection of downloaded images to cover the entire city's extent.

After building the mosaic, we executed supervised classification of land cover using a random forest (RF) classifier in GEE. The RF classifier is a machine learning algorithm that repeatedly fits decision trees (the 'forest') to random subsets of a training data set to inform classifications of the broader test data. It is a popular method in remote sensing for its accurate classifications, as well as its ability to handle large amounts of data while being insensitive to multicollinearity between spectral signatures among classes in the provided training samples [42]. We selected training polygons for the classification procedure randomly and equally among five classes: 'forest', 'low vegetation', 'built-up / developed', 'bare earth / tilled soil', and 'water'. Over the entire study area, 400 training polygons (80 per class) covering 1.98 km^2, approximately 0.1% of the total area, were manually drawn. We used an RF classifier with 30 decision trees to assign each pixel in the composite image to a land cover class, based on the reflectance values imparted from the original multispectral images. We then converted the raster image containing classification data into polygon spatial information with ArcGIS Pro 2.7.2 [43], calculated area and perimeter of all forest patches, and used the Near analysis tool in ArcGIS to calculate the nearest neighbour from each municipal address point to the closest forest patch edge within the City of Ottawa boundaries [44] to represent the degree to which developed land interfaced with woodland.

To account for areas presenting entomological hazard, only forest patches greater than 0.01 km^2 were included in the subsequent analyses, after Mcclure & Diuk-Wasser and Allan et al. [33,45] We used a set of landscape fragmentation indices [46] as measures of forest structure and fragmentation in each neighbourhood: the number of forest patches, the mean forest patch size, the proportion of the neighbourhood area that is covered by forest, the edge-to-area ratio (the

amount of forest edge, in km/km^2 of neighbourhood forest area), and forest edge density (the amount of forest edge, in km/km^2 of the total neighbourhood area). The use of edge-to-area ratio allowed us to compare local forest structures of similar size that exhibit very different shape complexities, as illustrated in Figure 4.2. In this example, all three forest patches are of comparable size. It is their shapes and, as a result, their perimeters, which are important to consider. In forest patch A, a contiguous forest patch is 'carved into' to create residential enclaves that back into the existing woodlands and provide many residents direct access to greenspace. The complexity of the resulting shape is represented by its edge-to-area ratio of 42.6 km/km^2. By comparison, each of forest patches B and C both exhibit somewhat complex geometries yet have structures that are far less disturbed by the surrounding land use.

Figure 4.2 Forest patches of comparable size demonstrating differences in forest shape complexity. Figure was produced with ArcGIS Pro 2.7.2 software and includes the area, perimeter, and edge-to-area ratio of each forest patch depicted.

4.2.5.4.3 Statistical analysis

For descriptive analysis, we calculated Pearson Chi-square statistics to evaluate significant differences ($\alpha = 0.05$) in means of each variable between neighbourhoods with no residential Lyme disease cases and those with at least one. We considered potential associations between each indicator and residential Lyme disease incidence independently in univariable analyses. We then evaluated selected pairs of these variables, including their interactions, in multivariable analyses. The chosen variable pairs reflect relationships hypothesized *a priori* between the neighbourhood characteristics and the occurrence of Lyme disease from residential exposure, as

outlined in Table 4.2. We calculated Pearson correlation coefficients between pairs of independent variables to uncover any potential collinearity in the hypothesized relationships (Figure S4.1). To further ensure collinearity did not influence the models, we used R package *mctest* version 1.3.1 [47] to calculate variance inflation factors for each independent variable in each model in the absence of interaction terms.

Table 4.2 Rationale for modelled relationships between neighbourhood social and ecological characteristics.

Modeled relationship	Variables		Rationale
1	Proportion forested landcover	Mean forest patch size	Areas with high proportion of forest cover but smaller mean forest patches can translate to more non-forested areas bordering woodlands, which presents increased potential for local exposure opportunities compared to where high proportion of forest cover is dominated by large, expansive forests.
2	Number of forest patches	Forest edge-to-area ratio	Higher numbers of geometrically complex forest patches in the terrain may be an indicator of more edge shared with non-forested lands compared to other forest stands, with wider access allowing for potentially greater risk of local tick exposure.
3	Number of forest patches	Mean forest patch size	Higher numbers of forest patches with greater average size in the neighbourhood translate to greater reservoir host populations and suitability of disease transmission cycles.
4	Mean forest patch size	Forest edge-to-area ratio	Neighbourhoods with high average forest patch size and high forest patch shape complexity can sustain high reservoir host populations as well as provide increased opportunities for local tick exposures through more forest edge access.

5	Median household income	Forest edge-to-area ratio	Neighbourhoods with high median household income where larger housing lot sizes border long, complex forest edges contribute to increased opportunities for tick exposure risk.

We used a series of negative binomial (NB) generalized linear models (GLM) fit with a log link to identify socio-ecological factors associated with the occurrence of Lyme disease across Ottawa neighbourhoods. Derived from the Poisson-gamma mixture model, NB is ideal for modeling count-based data that exhibit overdispersion among observations. We chose to use the NB model over Poisson because the variance of the dependent variable was greater than the mean ($\mu = 1.07$, $\sigma^2 = 6.67$). As the Lyme disease count totals across Ottawa neighbourhoods were generally low, we further tested for overdispersion with the Poisson dispersion statistic, calculated as the Pearson chi-square statistic divided by the model's degrees of freedom, in each univariable GLM. Since dispersion was greater than 1.0 in all cases ($P > 0.01$) it was reasonable to proceed with the standard negative binomial distribution for all models, under the assumption that heterogeneity of observations across neighbourhoods is the cause of overdispersion in the data [48].

Spatial autocorrelation (SA) is a property whereby observed values of a variable between adjacent areas may exhibit more systematic similarity (positive SA) or dissimilarity (negative SA) than would be expected by random chance. When SA is unaccounted for, the chance of a Type I error increases due to violation of the assumption of independence between samples [49]. With the *spdep* package [50] for R 4.0.3, we calculated Moran's I with a weights matrix based on queen contiguity (i.e. neighbourhoods were adjacent if they shared any edge or corner of their

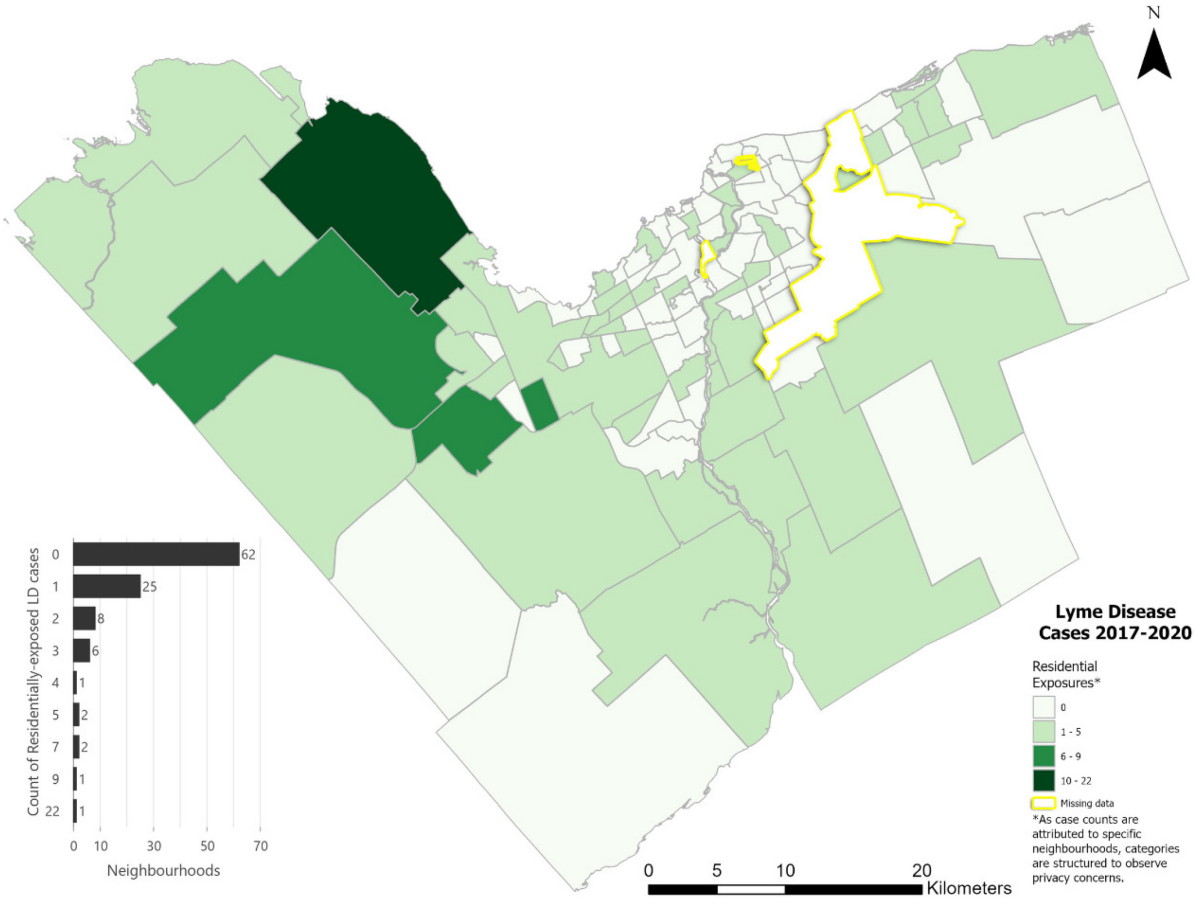
boundaries) and Monte Carlo randomization using 999 simulations to evaluate spatial dependence of the observed number of Lyme disease cases between neighbourhoods. Moran's I for the count of Lyme disease cases was weak (0.33) but significant (P = 0.001), indicating that neighbourhoods located close to one another tended to exhibit similar incidence (Table S4.1). To account for this spatial autocorrelation, we used Moran eigenvector spatial filtering [51] wherein the spatial dependence of the neighbourhood Lyme disease counts (i.e., the weights matrix) was decomposed into eigenvectors and included in GLMs as independent variables that allowed us to filter spatial autocorrelation of the neighbourhood-level observations out of model residuals [52,53].

We used the *MASS* package version 7.3.55 [54] to fit negative binomial GLMs with the first-order queen's contiguity Moran's eigenvector as a spatial filter constructed using the *spatialreg* package version 1.2.6 [51]. For all models, to adjust for variations in population size at the neighbourhood level, we set a constant offset term equal to the natural logarithm of each neighbourhood's total population estimate from the 2016 Statistics Canada census. We calculated incidence rate ratios (IRRs) and the associated 95% confidence interval for all variables by exponentiating the coefficients from each model and assessed model fits using the Akaike Information Criterion (AIC).

4.2.6 Results

A total of 581 Lyme disease cases were reported to Ottawa Public Health from 2017 to 2020 across the 112 neighbourhoods of Ottawa, Ontario. Forty-four (44) cases did not provide a

suspected exposure location and for 3 patients there was no home location available and therefore could not be geocoded. Of the cases with complete spatial information (n = 534; 92%), 427 (80%) named only one location where their tick encounter may have occurred. Exposures that occurred at the patient's residence or another location within the same neighbourhood accounted for 118 (22%) cases, while 73 cases (14%) cited exposure elsewhere within Ottawa and 343 cases (64%) attributed their exposure to travel outside of the city (Table S4.2). Twenty-two (4%) residential Lyme disease cases occurred in one neighbourhood (Dunrobin), whereas 25 (23%) neighbourhoods only had a single residential case (Figure 4.3). Sixty-two (57%) neighbourhoods, mainly within the Greenbelt area, had no reported Lyme disease cases attributed to residential exposure.



2187

2188 **Figure 4.3** Residential Lyme disease case counts by Ottawa neighbourhoods (2017-2020).

2189

2190 Descriptive statistics for all variables are presented in Table 4.1. Neighbourhood median
2191 household income had a citywide mean of $75,736 (± $24,280 SD) and was higher ($p = 0.05$) in
2192 neighbourhoods with at least one residential Lyme disease case ($81,098) compared to where
2193 there were none ($71,844). The RF classifier provided near perfect agreement between the
2194 classification and the reference mosaic of PlanetScope imagery ($\kappa = 0.977$). Based on its
2195 classification result, the highest proportion of forested area among neighbourhoods was 81.7%
2196 with a mean of 17.4% (± 18.6% SD). Neighbourhoods where residential Lyme disease cases

occurred had just over 6.5% more forest cover on average than those with no cases. The number of forest patches in a single neighbourhood ranged from 0 to 261, while neighbourhoods with at least one case averaged 36 more patches than other neighbourhoods. The mean forest patch size was also larger where residential Lyme disease cases occurred, exceeding the mean size in other neighbourhoods by 2.25 km^2. Within-neighbourhood ratio of forest edge to area ranged from 0 to 1,778.6 km/km^2 with a mean of 739.4 km/km^2 (± 390.3 SD). Neighbourhoods where residential Lyme disease cases occurred averaged 680.2 km/km^2 in forest edge-to-area compared to 782.3 km/km^2 among neighbourhoods without cases (P = 0.2). The density of forest edge compared to neighbourhood area was 8.7 km/km^2 on average (± 6.7 SD), with a lower limit of 0 in neighbourhoods that had no forest patches larger than 0.01 km^2 and a maximum of 40.8 km/km^2. Nearest neighbour analysis measuring the shortest distance from each municipal address to the closest point along a forest edge resulted in neighbourhood averages that ranged from 3.8 to 758.1 metres, with a mean nearest neighbour distance of 259.7 (± 174.5 SD) metres among all neighbourhoods.

4.2.6.1 Univariable model results

Residential Lyme disease incidence was positively associated with median household income, number of forest patches, proportion of neighbourhood classified as forest, forest edge density, and mean forest patch size (Table 4.3). Conversely, it was negatively associated with forest edge-to-area ratio and average nearest forest edge distance. These results suggest significant associations between residential Lyme disease incidence and the socio-ecologic composition of the neighbourhoods in which these cases occur. The factor with the strongest positive association

is mean forest patch size (IRR: 2.96, $p < 0.001$), where the model predicts nearly three times higher residential Lyme disease incidence in neighbourhoods where forest patches are one standard deviation (6.76 km2) larger on average compared to where they are average size in Ottawa (2.57 km2).

Table 4.3 Negative binomial generalized linear model results as incidence risk ratios (IRR) and 95% confidence interval of Lyme disease risk from residential exposure for selected variables.

Variable[a]	IRR estimate (95% confidence interval)	*P*
Median household income (after tax)	2.28 (1.46, 3.67)	< 0.001
Number of forest patches	2.31 (1.75, 3.15)	< 0.001
Forest edge-to-area ratio	0.40 (0.26, 0.58)	< 0.001
Proportion of forested area	2.47 (1.85, 3.37)	< 0.001
Mean address-forest edge distance	0.44 (0.3, 0.62)	< 0.001
Forest edge density	2.35 (1.55, 3.61)	< 0.001
Mean forest patch size	2.96 (2.04, 4.54)	< 0.001

[a] All variables are standardized; Incidence rate ratio estimates represent the effect of a one standard deviation increase in measurement.

4.2.6.2 Multivariable model results

Table 4.4 summarizes results for the hypothesized multivariable relationships between residential Lyme disease incidence and selected variables (detailed in Table 4.2), both aspatial and with spatial filtering applied. The association of mean forest patch size with predicted residential Lyme disease risk was greatly amplified through interactions with neighbourhood proportion of forested area (model 1) and edge-to-area ratio (model 4), compared with its result in univariable analysis. Interaction terms were statistically significant in three of the five hypothesized relationships (models 1, 4, and 5). We present the interaction plots for these three models in

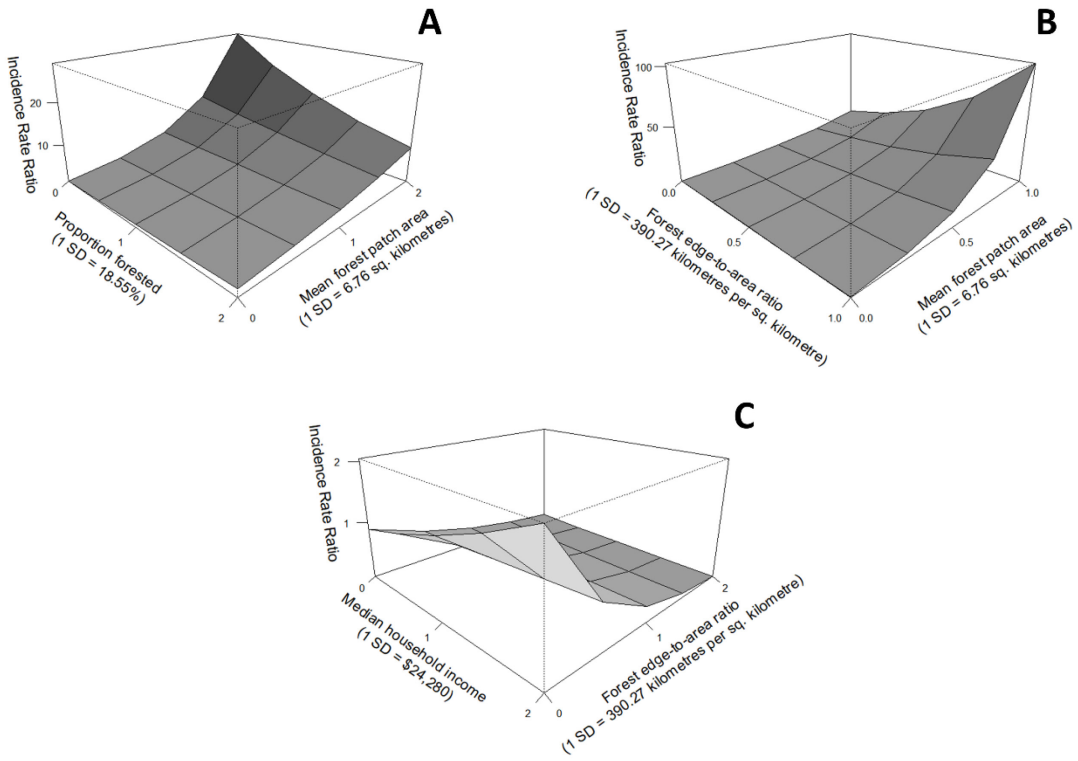
Figure 4.4 to aid interpretation of the total and marginal effects of the association between each variable and residential Lyme disease incidence. After adjusting for spatial autocorrelation, model 4 performed best as it had the lowest Akaike Information Criterion score (AIC, 252.02), followed closely by model 1 (262.71). Multicollinearity was not detected between individual independent variables by variance inflation factor tests in any of the five modeled relationships.

Table 4.4 Incidence rate ratios and 95% confidence intervals for negative binomial (NB) multivariable generalized linear models, with spatial filtering, of hypothesized neighbourhood characteristic relationships including interaction terms.

		NB model with spatial filtering	
Model	**Variables**[a]	IRR (95% CI)	*P*
1	Proportion forested land cover	1.58 (1.05, 2.36)	0.022
	Mean forest patch size	5.14 (2.49, 11.22)	< 0.001
	Moran eigenvector filter	8.71 (0.51, 153.03)	0.114
	Proportion forest x Forest patch size	0.60 (0.46, 0.77)	< 0.001
	AIC	262.71	
2	Forest patches (> 0.01 km^2)	1.19 (0.49, 2.89)	0.704
	Edge-to-area ratio	0.53 (0.32, 0.86)	0.013
	Moran eigenvector filter	8.57 (0.28, 246.87)	0.140
	Forest patches x Edge-to-area ratio	0.59 (0.25, 1.37)	0.231
	AIC	273.34	
3	Forest patches (> 0.01 km^2)	1.77 (1.30, 2.43)	< 0.001
	Mean forest patch size	1.81 (1.19, 2.87)	0.0029
	Moran eigenvector filter	0.01 (0.00, 0.08)	< 0.001
	Forest patches x Forest patch size	0.78 (0.57, 1.07)	0.105
	AIC	258.07	
4	Mean forest patch size	12.51 (4.69, 33.89)	< 0.001
	Edge-to-area ratio	1.38 (0.86, 2.22)	0.179
	Moran eigenvector filter	0.01 (0.00, 0.05)	< 0.001

	Forest patch size x Edge-to-area ratio	4.54 (2.29, 9.16)	< 0.001
	AIC	252.02	
5	Median household income ($000)	1.52 (1.03, 2.24)	0.035
	Edge-to-area ratio	0.41 (0.27, 0.62)	< 0.001
	Moran eigenvector filter	0.00 (0.00, 0.14)	0.003
	Median household income x Edge-to-area ratio	0.59 (0.38, 0.93)	0.022
	AIC	313.45	

2246 [a] All variables are standardized; Incidence rate ratio estimates represent the effect of a one standard deviation increase in
2247 measurement.
2248



2249

2250 **Figure 4.4** Interaction plots where vertical height represents the incidence rate ratio for the combined
2251 effect from changes, in standard deviation units, to proportion of forest cover and mean forest patch size
2252 (A), forest edge-to-area ratio and mean forest patch size (B), and median household income and forest
2253 edge-to-area ratio (C) in negative binomial GLMs with spatial filtering. The slope along each edge gives
2254 each variable's marginal effect.

Univariable analyses of mean forest patch size and edge-to-area ratio demonstrated opposing associations with residential Lyme disease incidence. However, in model 4 (Table 4.4) these two factors exhibit a significant and synergistic interaction, such that the highest residential Lyme disease incidence was predicted in neighbourhoods with high edge-to-area ratio (forest shape complexity) and large average forest patch sizes (Figure 4.4B). With this interaction, the association of edge-to-area ratio reversed direction and that of mean neighbourhood forest patch size was greatly amplified. In practical terms, this means that neighbourhoods where greater ecotonal area exists – large woodland areas with peripheries that interface with various land covers (i.e., Figure 4.2A) – are predicted to experience high Lyme disease incidence. While the independent and marginal effects of these factors were attenuated after adjustment for spatial autocorrelation, their associations remained strong and significant.

In contrast, the marginal effect contributed by the interactions in models 1 and 5 (Table 4.4) reduced the association of each variable with predicted incidence (Figures 4.4A & 4.4C). In model 1, residential Lyme disease incidence is highest when neighbourhood proportion of forested area is low and mean forest patch area is high (Figure 4.4A). When mean forest patch size is low (or more fragmented) there is a very slight positive relationship between proportion of forested area and incidence. However, with larger mean forest patch sizes (1.5 or more standard deviations above average), the relationship between proportion of forested area and incidence shows a negative trend. Thus, we might expect fewer cases of Lyme disease resulting from residential exposure in neighbourhoods where expansive, contiguous forested areas dominate the landscape compared to neighbourhoods containing one or more large patches but with proportionally lower forest cover. This makes sense as, in the former case, the proportion of

developed land would be lower and represent less opportunities in the neighbourhood area for tick encounters.

While statistically significant ($p = 0.02$), the interaction in model 5 between mean neighbourhood household income and neighbourhood forest edge-to-area ratio exhibited the weakest model fit. Though the model seems to suggest that increases in forest complexity suppress an association between high neighbourhood income levels and residential Lyme disease risk (Figure 4.4C), the decline in model performance after adjustment for spatial autocorrelation (**Δ**AIC: 32.46) suggests this should be interpreted with caution.

The number of forest patches in a neighbourhood was the only variable that was not involved in a statistically significant interaction (models 2 and 3, Table 4.4). In each of these models the marginal effect of interaction terms appears to suppress the effects of each independent variable alone. In model 2, greater numbers of forest patches in a neighbourhood show a slight association with increased residential Lyme disease incidence, which is further dampened as forest shapes increase in complexity. By comparison, the positive association between number and size of neighbourhood forest patches with residential Lyme disease incidence in model 3 are stronger than a negligible interaction effect. In this case neighbourhoods with many forest patches, large woodland areas, or both are predicted to have higher Lyme disease incidence from local exposures. This suggests that while the number and size of these forest patches are strongly and independently associated with residential Lyme disease incidence in Ottawa neighbourhoods, their combined effect is less evident.

4.2.7 Discussion

This study provides the first assessment of neighbourhood-level socio-ecological characteristics associated with residential Lyme disease risk in a major Canadian population centre. Across the entire study period (2017-2020), just over one-fifth of Lyme disease cases reported to Ottawa Public Health believed they were exposed on their own property or elsewhere in the neighbourhood where they lived. While most Ottawa cases during this period were not considered residential per our definition – other suspected exposure locations include natural areas outside the patient's home neighbourhood, out to the broader eastern Ontario region, or further abroad – it is important to note that residential Lyme disease exposure may increase in importance with ongoing climate and land use change. Observations of ticks in gardens and mown lawns in areas with established tick populations demonstrate that occurrence of "backyard" encounters may increase [55,56]. This trend has two important drivers. First, the emergence and establishment of tick populations in new locations in Canada has been demonstrated through surveillance and is likely to continue in northern latitudes [11,17]. Second, between urban area growth and infrastructure development, the interface between inhabited and natural landscapes will become more intertwined. Thus, it is important to identify characteristics of the urban landscape that may be relevant to public health planning for tick-borne diseases at a local level and consider them in zoning and official plans. A novel aspect of our analysis is the examination of statistical interactions between pairs of neighbourhood forested area measurements and the incidence of residential Lyme disease at the neighbourhood scale. The modeled interactions provided additional insights into the associations between forest fragmentation, forest shape complexity, and residential Lyme disease risk compared with when these factors were considered independently.

We showed that higher Lyme disease incidence is associated with greater forest patch size within local neighbourhoods (Table 4.3), consistent with what was previously observed at the level of municipalities [25]. In neighbourhoods where the average forest patch size is just over 9 km^2, there was a nearly threefold increase in the incidence of residential Lyme disease compared to neighbourhoods where forest patches averaged roughly 2.5 square kilometres in size. While Allan et al. [33] demonstrated that dramatically higher Lyme disease risk may result from decreasing forest patch size, their focus was on whether higher entomological hazard posed by increased density of infected nymphal ticks was present in smaller compared to larger forest patches. Our studies are not directly comparable as the response variables and scale of analyses are different. Statistical results from our analysis of cases are dependent on the spatial scale and zonal configuration of the ONS neighbourhoods within which the cases are aggregated. Such differences are induced by the Modifiable Areal Unit Problem in geographic analysis [57] and should be seen as a scale-dependent analysis that is different from that of Allan et al. Where they identify the association between tick hazard present in individual forest patches and the size of those patches, we evaluated residential Lyme disease incidence associated with neighbourhood-mean patch sizes. Furthermore, our multivariable analysis revealed that the effect of mean forest patch size was significantly amplified through the effects of forested land cover proportion or forest shape complexity (edge-to-area ratio) within neighbourhoods (models 1 and 4). Our results suggest that greater average patch sizes have a pronounced association with residential Lyme disease risk when the overall proportion of forested area in the neighbourhood is less than twenty percent. Since our exposure criteria was limited to encounters on patients' properties or elsewhere in the same neighbourhood, our results highlight that careful consideration of how

2347 woodlands and larger forest patches are integrated into the neighbourhood landscape, as well as
2348 how they are used by nearby residents, should be exercised.
2349
2350 Our analysis of forest edge-to-area ratio also showed an association with predicted incidence of
2351 residential Lyme disease cases, supporting prior findings of a negative correlation between
2352 specific landscape edge definitions and Lyme disease incidence at the county level in the United
2353 States [27]. A one standard deviation increase (390 km/km^2) of this ratio above the mean was
2354 associated with 60% fewer cases compared to neighbourhoods with Ottawa-average forest
2355 complexity. However, analysis of the combined effect of edge-to-area ratio with average forest
2356 patch size (model 4, Table 4.4) allowed us to examine the effect of forest complexity
2357 disentangled from forest area by holding average patch size constant. This revealed a more
2358 complex relationship of landscape designs with high edge-to-area ratio. Where development
2359 encroaches on larger forest patches, increasing forest edge and, presumably, the risk for human
2360 tick encounters in the neighbourhood at those edges, the interaction model predicted higher
2361 Lyme disease incidence resulting from local tick exposures. Figure 4.2A illustrates one
2362 hypothetical example of this – a large woodland that is carved up but not fragmented, allowing
2363 more residential properties and additional opportunities for exposure through new woodland
2364 interface. By comparison, Figures 4.2B and 4.2C depict forest patches of similar size to Figure
2365 4.2A but with much smaller edge-to-area ratios, which is associated with lower residential Lyme
2366 disease risk according to model 4 results. Though our analysis does not specify the types of edge
2367 contrast (e.g., forest-low vegetation, forest-developed) in our estimation of forest edge
2368 measurement, the general effect of edge within neighbourhood areal units is significant,
2369 indicating greenspace that exhibits complex shapes and its integration with other landscape types

merits further exploration – particularly in developed residential areas where tick populations are established.

Our results also suggest that higher Lyme disease incidence occurs in wealthier neighbourhoods. In our univariable analyses, a neighbourhood with a median after-tax household income of approximately one hundred thousand dollars per year had more than twice as many cases of residential Lyme disease than neighbourhoods with the mean income level ($75,736). This is consistent with previous studies, which associated higher socio-economic levels with greater Lyme disease risk regardless of where the tick encounter occurred [58]. Unexpectedly, our interaction model evaluating household income and forest edge-to-area ratio revealed a negative association of their combined effect with the incidence of residential Lyme disease cases. When neighbourhoods exhibit a city-average level of forest shape complexity (e.g., 739.35 km/km^2), increases to neighbourhood median household income result in higher Lyme disease incidence. One interpretation for this result is that in wealthier peri-urban communities, where large residential lots may border tracts of woodland, Lyme disease risk is higher. Yet, more complex neighbourhood forest structures drastically reduce the effect contributed by neighbourhood socio-economic levels – counter to the relationship hypothesized *a priori*. It is possible that forests with greater edge occur in areas with more residential properties and thus smaller lot sizes, which is not captured by the aggregated nature of these data. Property-level effects and resident behaviours (e.g., lawn maintenance, adoption of preventive measures) could further confound a potential relationship in neighbourhoods characterized by high socio-economic levels and complex forest structures. Higher socioeconomic status also generally confers increased access and use of healthcare services [59] and it is possible that healthcare access inequality

might confound the observed effects due to differences within or between neighbourhoods. Furthermore, this model exhibited a lack of fit and residual spatial autocorrelation after spatial filters were applied, suggesting that while the combination of these values was significant in our study location it was not fully independent of the underlying spatial process or the definition of our variables at the chosen level of aggregation. Additional research at increased resolutions – focusing on details at the residential property level – could be helpful to identify the effects involved.

These results indicate a significant association with residential exposure risk in more heavily forested neighbourhoods with greater levels of forest shape complexity, or where large patches of forest are interspersed with and broken up by developed land. It is also true of wealthier peri-urban communities, where, in cities such as Ottawa, such neighbourhoods are comprised mainly of single-family homes, often situated on lots bordering tracts of woodland. For urban centres like Ottawa, where residential expansion into woodland areas is an alternative to intensification, this emphasizes that community design and structure are connected to local Lyme disease risk. Thus, community landscape composition warrants consideration in vital public health risk assessment. Urban development and greening initiatives will produce changes in the distribution and structure of forested land, particularly near the outer perimeter of municipal boundaries. It is important that these associations between local Lyme disease risk and landscape configuration are explored in settings where tick populations are established, through active surveillance to understand the impacts that neighbourhood development may have on entomological hazard and exposure risk through longitudinal evaluations.

A notable strength of our study is that we assessed the association between physical area and observed Lyme disease incidence at the neighbourhood scale – which may better reflect specific impacts from human alteration of the landscape. The neighbourhood scale also represents a suitable population size for cost-effective and targeted health intervention campaigns. Furthermore, this study leveraged recent PlanetScope satellite imagery to classify land cover and produce current estimates of local forested area. PlanetScope images have a much higher spatial resolution than 'off-the-shelf' land cover data products, which are typically generated from multiple sources and resolutions for wider areas with an update schedule of five to ten years. Our results demonstrate that these products are assets for future studies that broaden the land use classifications to include edge contrast types as well as longitudinal image analysis to evaluate local risk over time.

The nature of the available disease surveillance data presented several challenges to our statistical analysis. First, as Lyme disease is an emerging public health concern in the Ottawa region, reported cases are relatively low compared to other regions where transmission cycles of *B. burgdorferi* have been active for a longer period. Even aggregated to the neighbourhood scale and across four years, incidence was low (n = 581). In our study, it is lower still because our study focused on cases that occurred – to the patient's best recollection – at their residence or within the same neighbourhood; nearly 80% of Lyme disease cases in Ottawa suspected their exposure occurred away from their home neighbourhood. In the northeast United States, it is commonly accepted that most tick exposures resulting in Lyme disease occur on residential properties [60], however, there is little evidence as to the true difference in magnitude of risk from residential, recreational, and occupational exposures [58]. In contrast, recent intervention

control studies on residential properties [61,62] found no reduction in tick encounters or tick-borne disease incidence, suggesting that exposures occurring beyond the residential yard are more frequent than expected. While it is possible that misclassification resulting from self-report of the 'most likely' location impacts the case totals for some neighbourhoods, most Lyme disease cases (80%) reported to Ottawa Public Health specified only one location despite the opportunity to identify up to five. It is possible that recall bias may differ across neighbourhood types (i.e., urban, suburban, rural), wherein suburban and rural residents have different levels of perceived risk from ticks on their own property while those who have a lower perception of property-level risk might seek to explain their encounters through recreational activities that occurred off-property; such heterogeneity in attitudes could produce biased parameter estimates. Another possibility is that residents of Ottawa are more at risk of recreational exposures compared to other municipalities due to the proximity and integration of the Greenbelt across neighbourhoods. Furthermore, tick populations are still emerging in Ottawa and are more likely to be uneven in distribution compared to regions in the United States where prevailing exposure locations are residential [17]. However, by aggregating to the level of neighbourhood, rather than assigning exposure to reported point locations, we mitigated the effect of patient recall error commonly associated with tick bite encounters [63]. This also aligned our analysis to a scale relevant for different Lyme disease interventions [64]. Additional studies that perform active tick surveillance on residential properties and neighbourhoods across the continuum of developed, herbaceous and woodlands land cover types would help increase our understanding of whether property-level observations of *B. burgdorferi*-infected host-seeking ticks follow patterns of Lyme disease outcomes reported to public health officials.

While Ottawa's status as an urban centre with emerging Lyme disease risk makes it a prime location for this analysis, investigations at the local scale in additional, similar municipalities would further illuminate the true relationship between neighbourhood landscape composition and residential Lyme disease risk. As municipalities plan for future growth while simultaneously responding to climate change, land development guidelines that consider public health impacts are required. While this study is most relevant to Lyme disease at present, the local effects observed may translate to the risk of other emerging tick-borne diseases (e.g., anaplasmosis, *B. miyamotoi*, alpha-gal syndrome, ehrlichiosis, babesiosis) considering the expanding range of additional tick species typically found only in southern latitudes [65,66].

This research quantifies aspects of neighbourhood forests that are important in the context of residential Lyme disease risk in areas of tick habitat expansion. Specifically, these findings highlight significant interactions between neighbourhood-level landscape characteristics – a scale that better reflects the characteristics of local communities – that should be explored further within the context of landscape development and planning guidelines. Although the hypothesized model including interaction with the socio-economic factor did not perform well, the presence of a statistically significant interaction encourages further research. The methods and results are relevant to similar urban areas experiencing outward expansion during a period of Lyme disease emergence. Our findings also reinforce recent studies that emphasize the importance of geographic scale for selection of appropriate types of Lyme disease interventions [64], including educational campaigns aimed at improving the behaviours and practices of residents that may make them otherwise vulnerable. Lastly, by characterizing neighbourhoods through socio-economic and landscape factors, this project has established a basis for future research and

predictive mapping efforts for residential areas threatened by invading ticks and emergent Lyme disease.

4.2.8 Acknowledgements

The authors would like to thank Dr. G. Gunn from the University of Waterloo for introduction to and assistance with Google Earth Engine which greatly helped the progress of this paper. We also thank Ottawa Public Health for the provision of disease surveillance data.

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4.2.9 Supporting Information

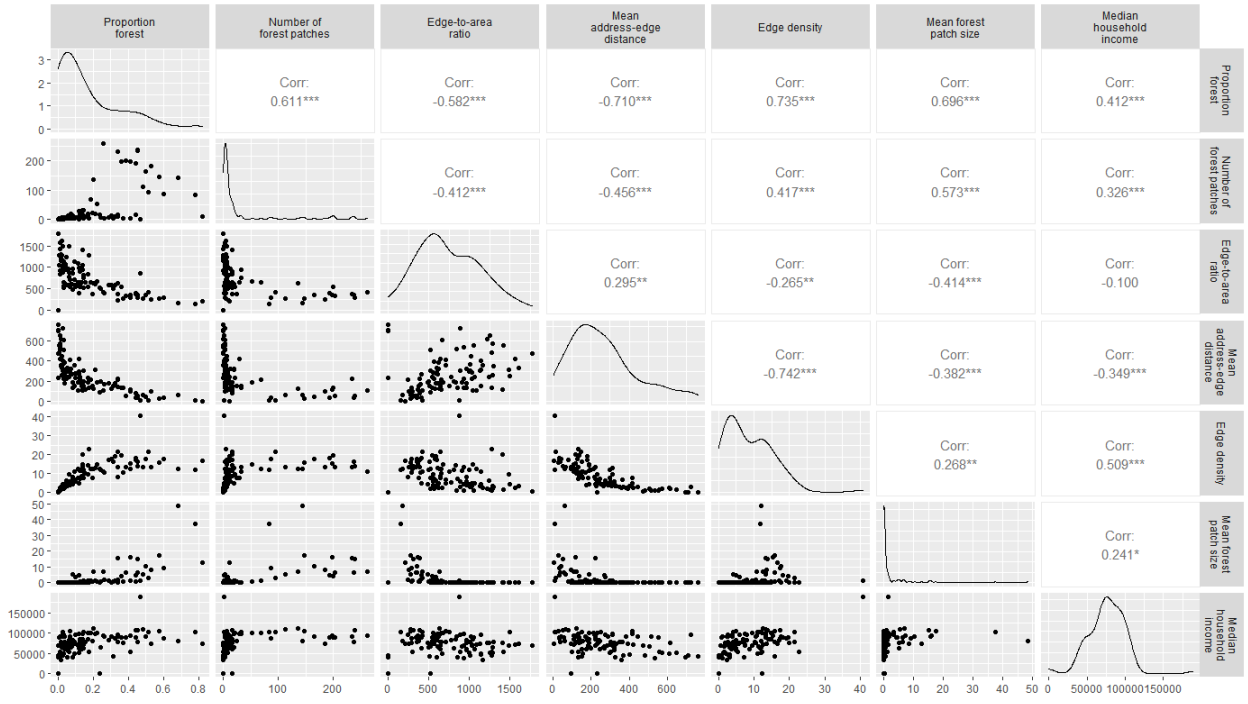

Figure S4.1 Pairwise correlation matrix between all independent variables explored through hypothesized relationships

Table S4.1 Moran's *I* and associated *P* values for tests of spatial autocorrelation using a Queen's case contiguity weight matrix and Monte Carlo simulations. Tests examined the similarity of residential Lyme disease (LD) cases and model residuals following negative binomial regression analyses between bordering neighbourhoods.

	Aspatial NB regression model *Moran's I* (*P*)	NB regression model with spatial filtering *Moran's I* (*P*)
Residential LD cases	0.33 (0.001)	
Model 1	0.02 (0.32)	0.002 (0.43)
Model 2	0.07 (0.13)	0.05 (0.19)
Model 3	0.03 (0.26)	-0.045 (0.66)
Model 4	0.08 (0.09)	-0.012 (0.48)
Model 5	0.19 (0.007)	0.11 (0.02)

Table S4.2 Lyme disease case demographics by primary exposure location classification, 2017-2020

	All cases (n = 581)	All cases with exposure data (n = 534)	Travel[a] exposures (n = 343)	Residential[b] exposures (n = 118)	Non-residential[c], Ottawa exposures (n = 73)
	n (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)
Mean Age ± SD	47.98 ± 41.96	48.55 ± 43.34	50.80 ± 51.41	46.43 ± 22.65	41.42 ± 20.86
Age Group					
< 14	80 (13.8)	73 (13.7)	42 (12.2)	20 (16.9)	11 (15.1)
15 – 24	30 (5.2)	26 (4.9)	14 (4.1)	3 (2.5)	9 (12.3)
25 – 34	48 (8.3)	44 (8.2)	27 (7.9)	10 (8.5)	7 (9.6)
35 – 44	72 (12.4)	64 (12.0)	39 (11.4)	16 (13.6)	9 (12.3)
45 – 54	105 (18.1)	93 (17.4)	63 (18.4)	20 (16.9)	10 (13.7)
55 – 64	125 (21.5)	119 (22.3)	81 (23.6)	20 (16.9)	18 (24.7)
65+	121 (20.8)	115 (21.5)	77 (22.4)	29 (24.6)	9 (12.3)
Gender					
Male	350 (60.2)	323 (60.5)	214 (62.4)	67 (56.8)	42 (57.5)
Female	231 (39.8)	211 (39.5)	129 (37.6)	51 (43.2)	31 (42.5)
Neighbourhood Type[d]					
Urban	176 (30.3)	165 (30.9)	129 (37.6)	12 (10.2)	24 (32.9)
Suburban	286 (49.2)	262 (49.1)	173 (50.4)	49 (41.5)	40 (54.8)
Rural	116 (20.0)	104 (19.5)	38 (11.1)	57 (48.3)	9 (12.3)

[a] Travel determined by location of primary (most likely) exposure location if more than one exposure location was named by the case.

[b] Residential exposure status determined by location of primary (most likely) exposure location, if more than one exposure location was named by the case, and matching that location to the neighbourhood of the home address.

[c] Non-residential cases are all cases that were not travel-related, as determined by location of primary (most likely) exposure location, who were not identified as being exposed at/near their home address.

[d] Individuals who provided no address information are omitted from neighbourhood type totals and proportions.

Table S4.3 Incidence rate ratios and 95% confidence intervals for aspatial negative binomial (NB) multivariable generalized linear models of hypothesized neighbourhood characteristic relationships including interaction terms

		Aspatial NB model	
Model	**Variables**[a]	IRR (95% CI)	*P*
1	Proportion forested land cover	1.47 (0.97, 2.21)	0.05
	Mean forest patch size	5.04 (2.37, 11.39)	< 0.001
	Moran eigenvector filter	n/a	n/a
	Proportion forest x Forest patch size	0.62 (0.47, 0.80)	< 0.001
	AIC	262.83	
2	Forest patches (> 0.01 km^2)	1.00 (0.43, 2.44)	0.99
	Edge-to-area ratio	0.50 (0.30, 0.83)	0.008
	Moran eigenvector filter	n/a	n/a
	Forest patches x Edge-to-area ratio	0.51 (0.22, 1.21)	0.136
	AIC	272.83	
3	Forest patches (> 0.01 km^2)	1.80 (1.18, 2.82)	< 0.001
	Mean forest patch size	2.30 (1.26, 4.61)	0.0012
	Moran eigenvector filter	n/a	n/a
	Forest patches x Forest patch size	0.79 (0.51, 1.23)	0.203
	AIC	269.56	
4	Mean forest patch size	24.27 (5.63, 118.91)	< 0.001
	Edge-to-area ratio	1.59 (0.84, 3.08)	0.116
	Moran eigenvector filter	n/a	n/a
	Forest patch size x Edge-to-area ratio	6.43 (2.20, 19.59)	< 0.001
	AIC	265.21	
5	Median household income ($000)	1.47 (0.96, 2.24)	0.049
	Edge-to-area ratio	0.45 (0.30, 0.66)	< 0.001
	Moran eigenvector filter	n/a	n/a
	Median household income x Edge-to-area ratio	0.63 (0.40, 0.98)	0.038
	AIC	280.99	

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Chapter 5

Knowledge, protective behaviour, and perception of Lyme disease risk in Ottawa, Ontario

5.1 Article preface

To explore the vulnerability component of local Lyme disease risk in the Ottawa, Ontario region, I conducted a survey of knowledge, attitudes, and practices (KAP) regarding Lyme disease among the city's adult residents. In addition to a survey instrument designed to align with those used in national studies and public health unit surveillance, I asked respondents to identify the woodland locations they visited most frequently on a map. With these responses, I determined the proportion of respondents who visited areas estimated to represent high Lyme disease hazard, according to an ecological niche model for *I. scapularis* ticks in southern Ontario and public health classifications of high risk outside this region. I used logistic regression models to identify characteristics and habits of respondents associated with high levels of Lyme disease knowledge and a high adoption rate of protective practices.

5.1.1 Author contributions

I designed the research question and the survey questionnaire with guidance from my supervisor, Dr. Manisha Kulkarni. I developed the methodology and performed all analyses, including spatial data relationships, data cleaning, and statistical modelling. All authors reviewed the first

draft of the manuscript and provided feedback on the structure of the findings and arguments presented.

5.1.2 Ethics approval and consent to participate

Written informed consent was obtained from all study participants via selection of an "I agree" option on a webform following their review of the informed consent agreement, required before the participant could proceed to the survey on the web platform on which it was administered. The University of Ottawa Health Sciences and Sciences Research Ethics Board reviewed and approved the survey protocol, as well as the procedure for obtaining informed consent (Certificate number H09-20-6104).

5.1.3 Article citation

Logan JJ**,** Sawada M, Knudby A. *et al.* Knowledge, protective behaviours, and perception of Lyme disease in an area of emerging risk: results from a cross-sectional survey of adults in Ottawa, Ontario. *BMC Public Health* **24**, 867 (2024). https://doi.org/10.1186/s12889-024-18348-6.

5.2 Article Content

5.2.1 Title

Knowledge, protective behaviours, and perception of Lyme disease risk in an area of emerging risk: results from a cross-sectional survey of adults in Ottawa, Ontario

5.2.2 Authors

James J. Logan

School of Epidemiology and Public Health, University of Ottawa, Ottawa, Canada

Michael Sawada

Department of Geography, Environment and Geomatics, University of Ottawa, Ottawa, Canada

Laboratory for Applied Geomatics and GIS Science, University of Ottawa, Ottawa, Canada

Anders Knudby

Department of Geography, Environment and Geomatics, University of Ottawa, Ottawa, Canada

Tim Ramsay

School of Epidemiology and Public Health, University of Ottawa, Ottawa, Canada

Ottawa Hospital Research Institute, University of Ottawa, Ottawa, Canada

Justine I. Blanford

Department of Earth Observation Science, Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, Netherlands

Nicholas H. Ogden

Public Health Risk Sciences Division, National Microbiology Laboratory, Public Health Agency of Canada, Saint-Hyacinthe, Canada

Manisha A. Kulkani

School of Epidemiology and Public Health, University of Ottawa, Ottawa, Canada

5.2.3 Abstract

Background: The number of Lyme disease risk areas in Canada is growing. In regions with emerging tick populations, it is important to emphasize peridomestic risk and the importance of protective behaviours in local public health communication. This study aims to identify characteristics associated with high levels of Lyme disease knowledge and adoption of protective behaviours among residents in the Ottawa, Ontario region.

Methods: A geographically stratified web survey was conducted in November 2020 (n=2018) to determine knowledge, attitudes, and practices regarding Lyme disease among adult residents. Responses were used to calculate: i) composite scores for knowledge and adoption of protective practices; and ii) an exposure risk index based on reported activity in woodlands during the spring-to-fall tick exposure risk period.

Results: Sixty percent of respondents had a high knowledge of Lyme disease, yet only 14% indicated they often use five or more measures to protect themselves. Factors strongly associated with a high level of Lyme disease knowledge included being 55 or older (Odds Ratio (OR) = 2.04), living on a property with a yard (OR = 3.22), having a high exposure index (OR = 1.59), and knowing someone previously infected with Lyme disease (OR = 2.05). Strong associations with the adoption of a high number of protective behaviours were observed with membership in a non-Indigenous racialized group (OR = 1.70), living on a property with a yard (OR = 2.37), previous infection with Lyme disease (OR = 2.13), prior tick bite exposure (OR = 1.62), and primarily occupational activity in wooded areas (OR = 2.31).

Conclusions: This study highlights the dynamics between Lyme disease knowledge, patterns of exposure risk awareness, and vigilance of personal protection in a Canadian region with emerging Lyme disease risk. Notably, this study identified gaps between perceived local risk and protective behaviours, presenting opportunities for targeted enhanced communication efforts in areas of Lyme disease emergence.

5.2.4 Introduction

Lyme disease is a tick-borne bacterial illness caused by *Borrelia burgdorferi* transmitted, in the North American northeast, through the bite of infected *Ixodes scapularis* (blacklegged) ticks [1]. It is the most common vector-borne disease affecting humans in North America and Europe [2,3]. Since Lyme disease became nationally notifiable in Canada, the annual number of reported cases has risen dramatically from 144 in 2009 to 3,147 in 2021 [4]. In Ottawa, Ontario, only six human cases were reported in 2008 compared to 190 in 2017, when public health officials first declared the region an at-risk area [5,6]. Recent studies in this region demonstrate that reproducing blacklegged tick populations are becoming established and that nearly thirty percent of ticks tested carry *B. burgdorferi* [7,8]. This rapid rise in human cases and concern for other emerging diseases highlights the importance of surveillance activities and efforts to improve public awareness in areas of emerging tick-borne disease risk [9,10].

Risk factors for Lyme disease are primarily related to individual behaviours involving tick exposure in areas with suitable tick habitat, such as woodlands, gardens, residential lawns, and public greenspaces [11]. In locations where blacklegged tick populations are becoming established, peridomestic risk is a legitimate and growing concern [12]. There is evidence that

public health interventions applied at the neighbourhood scale, comprised mainly of strategies aimed at reducing local entomological hazard, are likely effective [11]. However, even within such high-risk areas, the degree of correlation between tick abundance and human Lyme disease incidence at the level of residential properties is not well established [13]. Thus, tick control interventions cannot exclusively minimize risk, which highlights the need for actions taken by individuals to protect themselves. Household and personal protective practices are the most effective form of protection against tick-borne illnesses [14,15].

Actions that individuals can take to protect against Lyme disease include the application of insect repellents, wearing long clothing that covers the legs, tucking pants into socks, and performing tick checks after activity in areas with woodlands or long grass [15–17]. One review found that the effectiveness of these commonly used measures in reducing tick-borne disease rates was inconclusive and highlighted the insufficient collection of details regarding how these measures are practiced (e.g., use of one measure at the expense of others, selective combinations of measures) as a potential explanation [14]. Studies in areas where tick-borne diseases are endemic demonstrate that local Lyme disease incidence rates and perceived level of personal risk significantly influence the adoption of measures to prevent exposure and infection [18].

National awareness of Lyme disease has risen over time in Canada, but routine adoption of preventive practices is not high among Canadians [19,20]. While increased awareness is encouraging, the gap between awareness and the attitudes and behaviours contributing to the practice of personal protection raises concerns. The recent and ongoing expansion of suitable habitat for blacklegged ticks in Canada means that individual regions and, more directly,

municipalities are experiencing growing risk [8,21–23]. Even in the eastern United States, where Lyme disease is highly endemic, calls for local and environmental prevention measures have increased as the tick hazard has become more geographically widespread [15,24]. However, some evidence suggests that programs that plan and implement landscape controls to reduce tick populations are insufficient as they cannot uniformly reduce the risk by simply reducing the hazard [12,15]. This is because differences amongst people in the frequency of their interactions with tick habitat and use of protective behaviours contribute to variability in personal risk. It is therefore essential to identify characteristics of individuals associated with high exposure potential to target public health education campaigns that encourage the regular use of multiple protective measures.

As a model of disease prevention, Protection Motivation Theory (PMT) proposes that behavioural choices are a response to an individual's perception of the severity and their own vulnerability to disease, as well as whether they can reduce their own risk by adopting recommended actions [25]. Applied to Lyme disease prevention, PMT posits that people's motivation to adopt personal protective behaviours relies on them (1) perceiving Lyme to be a serious illness, (2) believing they have an elevated risk of exposure to ticks, and (3) trusting that the recommended action(s) will be effective in preventing Lyme disease. A Scandinavian study applying PMT to tick bite protection found that participants' belief in the seriousness of tick bites and Lyme disease predicted the adoption of protective measures, but that the perceived likelihood of exposure was associated with little change in the measures used [26].

As of 2017, 89 percent of adults in Ottawa were aware of Lyme disease [5]. Of those adults, just over 80 percent knew that Lyme disease results from tick bites and 62 percent reported using at least one protective measure to avoid exposure [5]. These rates are slightly lower than province-wide estimates reported in a 2014 national survey [19]. Though this level of Lyme disease awareness remains consistent at the Canadian level in 2023, little improvement regarding the adoption of behaviours aimed at tick bite prevention has occurred nationally [27]. A 2012 study evaluating the knowledge, attitudes, and practices for preventing Lyme disease held by the population of the Montérégie region of Québec found the epidemiological status of a region and behaviours of population subgroups were associated with the adoption of individual protective behaviours [18,28]. More recently, results from a survey of the neighbouring Estrie region in Québec demonstrated low adoption of preventive behaviours against tick bites with high sub-regional variability in this area of Canada experiencing high Lyme disease incidence [29,30]. Over the past five years, the establishment of the tick vector across the Ottawa municipal region has continued to increase and, though most Lyme disease cases reported to Ottawa Public Health suspect their tick encounter occurred during travel outside of the city, the characterization of peridomestic Lyme disease incidence in Ottawa neighbourhoods hints at localized hazard in the community [7,8,10,31].

The main objective of this study was to evaluate the level of Lyme disease knowledge and adoption of preventive practices in a Canadian municipality with emerging Lyme disease risk, namely Ottawa, Ontario. We further aimed to compare these observations across residents of five city regions (i.e., urban, rural, and three suburban areas defined in the city's east, south and west)

and population subgroups, as well as to identify individual characteristics associated with high levels of Lyme disease knowledge and adoption of protective behaviours.

5.2.5 Methods

5.2.5.1 Study Design

This cross-sectional study evaluated data collected through a web survey of Ottawa-area adults in November 2020. To be eligible, participants had to respond in either English or French. Canadian survey and analytics company Leger randomly invited participants from web panels of recruited Ottawa residents from November 5 to 25, 2020 [32]. Leger applied recruitment quotas to achieve a sample representative of the Canadian population. We used a stratified approach to ensure a balanced geographic representation across the city of Ottawa (i.e., urban, rural, suburban west, suburban south, and suburban east). We defined these five strata using statistical estimates of population density, walkability, and car commuting rates calculated by the Ottawa Neighbourhood Study (ONS) [33]. Following Statistics Canada definitions, we used population density to identify natural neighbourhoods of the ONS as either urban (greater than 400 people per square kilometre) or rural (less than 400 people per square kilometre) [34]. Following guidelines for categorizing suburbs established elsewhere [35] we sub-selected natural neighbourhoods where car commuter rates were above the City of Ottawa average (69%) or where ONS walkability measures implied moderate car dependence (i.e., scores between 20 and 50) as suburban. Using the Ottawa Greenbelt, an expanse of protected green space that stretches from east to west around the city, as a natural boundary, we then geographically subdivided the suburban neighbourhoods into areas east, south, or west of the urban core. Leger recruited

participants using the Forward Sortation Area (FSA) of their home addresses, using the FSAs to apply an approximation of these neighbourhood-based strata (Figure 5.1, Appendix B1). We aimed to obtain 370 responses from individuals aged 18 or older per stratum. This sample size would allow us to estimate, at a 95% confidence level and with a five percent margin of error, whether the proportion of Ottawa respondents with a high level of knowledge concerning Lyme disease was significantly different from sixty percent (a proportion that is slightly greater than that reported for the entire province of Ontario in a previous national survey [19]).

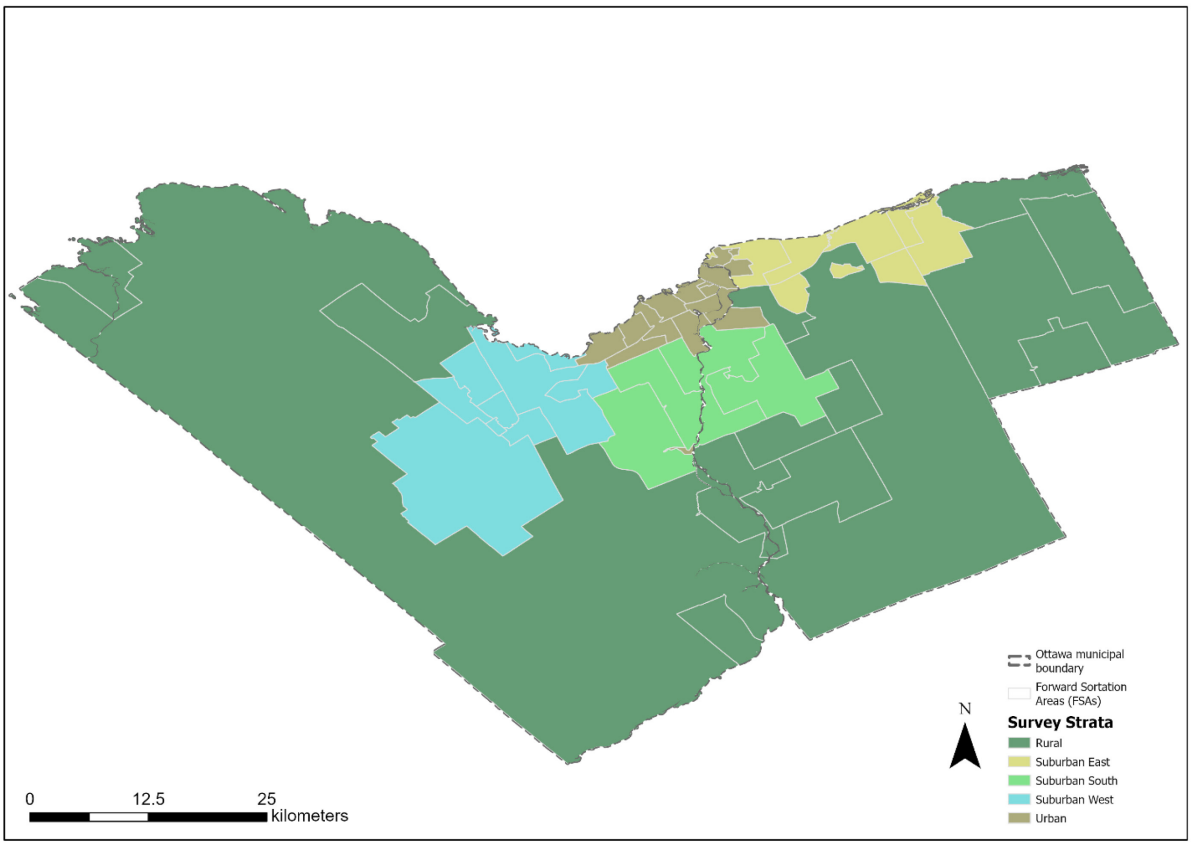

Figure 5.1 The geographic extent of survey strata defined by Canadian Forward Sortation Area of home address

5.2.5.2 Survey Instrument

We used a survey instrument designed for this study, adapted from questions used in a national study that evaluated Lyme disease knowledge, attitudes and practices of the Canadian population, as well as the Ottawa Public Health Rapid Risk Factor Surveillance survey for Lyme disease [20,36]. The questionnaire (see Appendix B2) included questions assessing respondents' knowledge concerning Lyme disease (e.g., its transmission, means of protection, symptoms, and treatment), perception of local risk, personal attitude towards possible Lyme disease prevention measures, personal adoption level of preventive behaviours (i.e., "In Ottawa I apply this measure to protect myself from Lyme disease:" always; frequently; rarely; never; sometimes I apply this measure, but not to protect myself from Lyme disease; does not apply to my situation; I prefer not to answer), as well as experience with tick bites and Lyme disease. We also asked respondents how frequently they visited "woodlands or areas with tall grass and/or shrubs" during the Lyme disease risk season from May to October of the survey year. To supplement this information on self-estimated exposure risk, we used an interactive map where respondents could identify up to three locations in "wooded areas or areas with tall grass and/or shrubs" as sites that they frequently visited over the same period and asked respondents to identify the primary reasons for such visits (e.g., work, recreation, camping). We also collected information on respondent demographics (age, gender, ethnicity, household income, and education level) to evaluate population subgroups. In analyses, we categorized respondents as White, Indigenous, or other based on their responses and guided by the Ontario Human Rights Commission's definitions of belonging to racialized population groups [37].

5.2.5.3 Data Analysis

5.2.5.3.1 Lyme disease knowledge and personal practices scores

We used composite scores to identify high levels of Lyme disease knowledge and adoption of personal practices. To obtain Knowledge Scores (KS) ranging from 0 to 4, we totalled the scores from four knowledge questions, including those on the transmission of Lyme disease to humans (i.e., "by a tick bite"), tick removal strategies (i.e., "pull it out with tweezers/forceps/etc."), the first symptom of Lyme disease in humans (i.e., any or all of "headache," "fever," "reddish rash on the skin," and "lethargy/malaise"), and existing treatment strategies (i.e., "with antibiotics in tablet form"). We assigned one (1) point for each question where only the correct option(s) were selected. For questions where participants selected 'other' as part of their response, we re-categorized the answer as correct if it was the only additional selection and the free response provided was an appropriate expansion of the expected answer (e.g., "twist it out with tweezers," "making sure to get the head out"). We similarly calculated personal practices scores (PS) between 0 and 7 based on the sum of scores for self-reported protective measures applied for the purpose of protecting against Lyme disease - one (1) point for each response of "always" or "frequently" using the following: "seeking and removing ticks on yourself after a stay in a forested area," "wearing long clothes that cover the legs," "using insect repellants with DEET or Icaridin on skin and/or clothing," "wearing clothing treated with an insecticide," "avoiding woodlands during the spring-to-fall risk period," "putting pesticides on my property," and "mowing the lawn regularly on my property." This approach was chosen to reflect regular use of the protective practice in question for the purpose of Lyme disease prevention.

In all analyses, we dichotomized scores to identify individuals with a high level of knowledge regarding Lyme disease and high adoption rate of personal protective practices, allowing comparability with other Canadian Lyme disease studies [18–20,38]. According to the common practice of using Bloom's cutoff points, a good score is considered 80% to 100% of possible answers scored as correct [39,40]. With total possible scores for KS and PS of 4 and 7, respectively, we defined our threshold for "High" scores with a modified Bloom's cutoff of 70% [33, 34]. With low totals for each domain and, in the case of protective measures, to allow that respondents may have specified "does not apply to my situation" for some practices, we used the modified cutoff point to remain conservative in what was considered "high". Thus, a KS of three or four represented an accuracy greater than 70% and was considered high Lyme disease knowledge. We similarly considered PS of 5 or greater to be "high", representing the personal adoption of more than 70% of the surveyed protective measures.

5.2.5.3.2 Exposure risk classification

From the specific locations volunteered by respondents as the wooded areas or areas with long grass that they frequented most, we identified whether individuals visited sites with high or low risk of blacklegged tick presence. We classified sites in Ontario with a 35% or higher probability of blacklegged tick presence, according to the ecological niche model developed by Slatculescu et al. [41], as "high" risk. This threshold was selected using the model output statistic aimed at maximizing model sensitivity and specificity - intended as a more conservative estimate of what

classifies as a “high-risk” area and follows from the use of model outputs in other studies [41–43]. Locations identified in Quebec and the United States were assigned “high” risk classification using previously established risk measures for the respective areas [44,45]. Using these location classifications and responses to the question, “How often did you visit woodlands or areas with tall grass and/or shrubs between May and October this year,” we assigned respondents to levels of an “exposure index.” We designated individuals as “negligible” risk when they identified their most frequent activity site in an area with a low likelihood of blacklegged tick presence or if they claimed to visit a high-risk area less than twice during the year. For the remainder of respondents who selected a high-risk area as the site of their most frequent activities in wooded areas, we assigned exposure risk levels of “low” (visited 2 to 10 times during the year), “medium” (11 to 25 times), and “high” (26 visits or more).

5.2.5.3.3 Statistical modelling

We performed all statistical analyses with R version 4.1.3. We calculated Pearson Chi-square statistics ($\alpha=0.05$) to test for significant differences between geographic and demographic groups. We used multivariable logistic regression to identify factors associated with high versus low Lyme disease knowledge and high versus low personal adoption of protective practices. First, we performed univariable logistic regression to test for an association of each independent variable with high KS and high PS separately. We retained factors associated with the dependent variable ($p<0.2$) for each outcome in the initial respective multivariable model [46]. With the MASS package version 7.3.60, we determined final multivariable models for high KS and PS using stepwise selection by Akaike Information Criterion (AIC). We forced gender, age group,

education level, and survey region in the final model as potential confounders and exposure index as the primary variable of interest for an association between exposure behaviour and the outcomes. In both models, we excluded individuals who responded "I prefer not to answer" to any questions used as independent variables in statistical analyses. To ensure that our definition of "high" PS was not skewed by scores that lacked responses for property measures which did not apply for some respondents (i.e., use of pesticides and mowing a lawn), we performed a sensitivity analysis of the final multivariable model for high PS that focused on the five individual practices, where the cutoff for a "high" PS in this scenario was 4 measures adopted. We used variance inflation factors, calculated using the mctest package version 1.3.1, to check for multicollinearity in the final models.

5.2.5.3.4 Spatial analysis

We used ArcGIS Pro 3.1.0 [47] to map the locations respondents identified as their most frequently visited wooded area. We assigned "high" or "low" blacklegged tick probability to each location by executing a spatial join of the activity sites identified by respondents to the data sources used to determine regional Lyme disease risk in Ontario, Quebec, and the United States described above. As most cases of Lyme disease reported in Ottawa disclose that their tick bite occurred during travel outside of the city [5, 31], we explored how far the wooded areas respondents visit most often were from where they live. To determine the distance travelled by each respondent to the site they visited most frequently, we geocoded each respondent to their home postal code. We then calculated the geodesic distance between their home and the activity location they provided based on the latitude and longitude of each location. We used the

Summary Statistics tool in ArcGIS to calculate the mean and variance of the distance travelled for all responses and separately for the groups who frequently travelled to locations with a "high" or "low" probability of blacklegged tick presence.

5.2.6 Results

5.2.6.1 Descriptive Statistics

A total of 2018 residents of Ottawa participated in this study, with the distribution of respondents roughly even across the five city strata (Table 5.1). The age group with the greatest proportion of respondents was 55 to 64 (23%, 472), while the fewest respondents were older than 75 (6%, 128). Of the seven family income classes, the highest number of respondents were from families earning $120,000 or more (29%, 515/1777) and of the four education level classes, the highest number of respondents were in the university-educated class (41%, 816/2000). Roughly one-fifth of respondents were Indigenous or other racialized Ottawa residents (Table 5.1). Overall, 251 respondents (12%) reported having experienced a tick bite, 74 (4%) reported having been personally infected by Lyme disease, and 531 (26%) knew someone who had previously been infected (Table 5.2). The proportion of respondents who believed Lyme disease to be very serious was 94%. Slightly greater than 40% of respondents reported that they felt at high or medium risk of contracting Lyme disease during the previous spring and summer, yet over half (1,082, 54%) stated that it was an outcome they worry about (Table 5.2). Approximately one-third did not believe it is easy to protect themselves against infection.

Table 5.1 Descriptive characteristics of survey respondents

	Ottawa, Ontario (2021 Census (%))[3]	n	% (95% CI)
Total	1,017,449 (100)	2018	100
Region			
Suburban East	205,776 (18.2)	419	20.8 (18.5, 23.0)
Suburban South	249,938 (22.2)	405	20.1 (17.8, 22.3)
Suburban West	161,625 (14.3)	381	18.9 (16.7, 21.2)
Rural	248,044 (22.0)	380	18.8 (16.6, 21.1)
Urban	262,187 (23.3)	433	21.5 (19.2, 23.7)
Gender			
Men	496,045 (48.8)	995	49.3 (47.0, 51.6)
Women	521,405 (51.2)	1015	50.3 (48.0, 52.6)
Other		8	0.4 (0.0, 2.7)
Age			
18 to 24	131,170 (12.9) [3]	139	6.9 (4.8, 9.1)
25 to 34	143,020 (14.1)	242	12.0 (9.9, 14.2)
35 to 44	135,410 (13.3)	303	15.0 (12.9, 17.2)
45 to 54	133,505 (13.1)	343	17.0 (14.9, 19.2)
55 to 64	135,260 (13.3)	472	23.4 (21.3, 25.6)
65 to 74	97,730 (9.6)	391	19.4 (17.2, 21.5)
75 or older	74,415 (7.3)	128	6.3 (4.2, 8.5)
Population Group[1]			
White	665,960 (65.5)	1592	79.8 (78.1, 81.5)
Indigenous	26,395 (2.6)	55	2.8 (1.1, 4.5)
Other	324,960 (31.9)	349	17.5 (15.8, 19.3)
Total		1996	100.0
Family Income[1,3]			
< $20,000	17,525 (4.3)	70	3.9 (1.6, 6.3)
$20,000 to $39,999	39,695 (9.7)	148	8.3 (6.0, 10.6)
$40,000 to $59,999	44,940 (11.0)	211	11.9 (9.6, 14.2)
$60,000 to $79,999	49,280 (12.1)	291	16.4 (14.1, 18.7)
$80,000 to $99,999	46,895 (11.5)	298	16.8 (14.5, 19.1)
$100,000 to $119,000	50,875 (12.5)[3]	244	13.7 (11.4, 16.0)
$120,000 or more	158,040 (38.8)[3]	515	29.0 (26.7, 31.3)
Total	407,250	1777	100.0
Highest Education Level[1,2,3]			
High school or less	284,135 (34.1)	296	14.8 (12.5, 17.2)
College	187,210 (22.4)	452	22.6 (20.3, 25.0)
University	225,720 (27.1)	816	40.8 (38.5, 43.2)
Graduate Studies	137,075 (16.4)	436	21.8 (19.5, 24.2)

Total	2000	100.0

[1]Respondents who answered "prefer not to answer" were excluded from totals and proportions.
[2]Respondents who answered "other" were excluded from totals and proportions.
[3]Ottawa population and demographics figures are Statistics Canada estimates for the Ottawa census subdivision (CSD) from the 2021 census [48]. Region population totals are calculated from Forward Sortation Area (FSA) boundaries which do not fall entirely within the Ottawa CSD; some FSAs classified as rural extend outside of this boundary. Demographics and age group definitions used by Statistics Canada do not directly align with those defined in the survey instrument used in this study (e.g., the survey targeted only adults while the youngest census group spans 15 to 24 years old). Census income groups represent the total number of Ottawa households with the identified income level.

Table 5.2 Number and proportion of respondents with knowledge, risk factors, attitudes, and practices regarding Lyme disease. Proportions reported are for column totals.

	All responses n (%)	KS ≥ 3 n (%)	KS < 3 n (%)
Total	2018 (100)	1211 (100)	807 (100)
High Lyme disease knowledge score (KS ≥ 3)	1211 (60)		
Transmitted by: tick bite	1710 (85)	1185 (98)	525 (65)
Best way to remove tick: pull with tweezers/forceps/other tool	1449 (72)	1109 (92)	340 (42)
First symptom(s): headache/fever/lethargy/reddish rash	1341 (66)	1117 (92)	224 (28)
Detected quickly, Lyme can be treated by: antibiotic tablets	916 (45)	833 (69)	83 (10)
Lyme disease attitudes[1,3]			
Feel at high or medium risk	789 (43)	543 (45)	246 (30)
Lyme disease is very serious	1885 (94)	1183 (98)	702 (87)
Easy to protect myself from Lyme disease	1316 (66)	881 (73)	435 (54)
There are great scientific uncertainties about Lyme disease	1081 (54)	706 (58)	375 (46)
Worry about contracting Lyme disease	1082 (54)	713 (59)	369 (46)
Personal protective measures[2]			
Seek and remove ticks after stay in forested area[3]	833 (60)	583 (48)	250 (31)
Wearing long clothes (including tucking pants into socks)[3]	1171 (66)	775 (64)	396 (49)
Use insect repellants with DEET or Icaridin[3]	972 (53)	636 (53)	336 (42)
Wear clothing treated with insecticides[3]	222 (13)	117 (10)	105 (13)
Avoid woodlands during spring-to-fall risk period[3]	737 (41)	451 (37)	286 (35)
Use pesticides on my property[3]	153 (9)	77 (6)	86 (11)
Mow lawn regularly on my property[3]	1281 (81)	852 (70)	429 (53)
High personal practices score (PS ≥ 5)	275 (14)	165 (14)	110 (14)
Exposure risk factors[3]			
Have access to outdoor yard (not responsible for maintenance)	436 (22)	226 (19)	210 (26)
Have access to outdoor yard (responsible for maintenance)	1315 (66)	883 (73)	432 (54)
Visited woodlands May-October			
More than 25 times	351 (17)	255 (21)	96 (12)
Between 11 and 24 times	312 (16)	205 (17)	107 (13)
Between 1 and 10 times	932 (46)	535 (44)	397 (49)
Never	415 (21)	213 (18)	202 (25)

Frequently travel to high-risk location	1314 (65)	825 (68)	489 (61)
Exposure index (high or medium)	565 (28)	392 (32)	173 (21)
Any travel to high-risk location(s)	1394 (69)	878 (73)	516 (64)
Travel 5 kilometres or less to visit wooded areas May-October	698 (35)	445 (37)	253 (31)
Travel > 10 kilometres to visit wooded areas May-October	541 (27)	350 (29)	191 (24)
Duration of activities in wooded areas typically ≥ 4 hours	256 (13)	144 (12)	112 (14)
Walk on trails/cleared paths during activities in wooded areas[2]	1294 (64)	834 (69)	460 (57)
Primary reason for visits to wooded areas in May-October			
Work	52 (3)	26 (2)	26 (3)
Recreation	1136 (56)	717 (59)	419 (52)
Birdwatching	153 (8)	84 (7)	69 (9)
Dog walking	337 (17)	205 (17)	132 (16)
Camping	117 (6)	76 (6)	41 (5)
Hunting	19 (1)	9 (1)	10 (1)
Cottage	167 (8)	112 (10)	55 (7)
Own a dog[3]	514 (25)	325 (27)	189 (23)
Personal history with ticks and Lyme disease[3]			
Ever had Lyme disease (self-reported)	74 (4)	38 (3)	36 (4)
Diagnosed with Lyme disease by doctor, specialist, naturopath, or private lab testing[4]	22 (30)	12 (1)	11 (1)
Know someone who has had Lyme disease	531 (26)	405 (33)	126 (16)
Ever bitten by a tick	251 (12)	169 (14)	82 (10)

[1]Totals include the number of respondents who answered "totally" or "somewhat agree".
[2]Totals include the number of respondents who answered "always" or "frequently".
[3]Excludes respondents who answered "Don't know", "I prefer not to answer", or "Does not apply to my situation".
[4]Excludes respondents who declared they have never had Lyme disease.

5.2.6.2 Lyme disease knowledge

60% of respondents exhibited a high level of Lyme disease knowledge (1,211, Table 5.2). Respondents aged 55 and older were most likely to demonstrate a high knowledge level (670, 68%) compared to those in the 18 to 34 and 35 to 54 age groups (44% and 58%, respectively, see Table S5.1) ($P < 0.001$). Differences in the proportion of subgroups with a high level of Lyme disease knowledge were also statistically significant by gender ($P=0.003$) and population group ($P < 0.001$). Correct response rates for the knowledge domain questions were consistently highest among respondents from the western suburbs or rural areas, while the proportion of correct

answers to each question was generally lowest among urban respondents (Figure 5.2A). One exception was knowledge about treatment for Lyme disease, which was the question with the most incorrect responses, regardless of the city survey region. A similar regional pattern was observed in residents' perceptions of personal risk (Figure 5.2D). Of all the knowledge questions, most respondents correctly identified that Lyme disease transmission to humans occurs via tick bites (85%). By comparison, less than half (45%) answered that Lyme could be treated with antibiotic tablets if detected quickly.

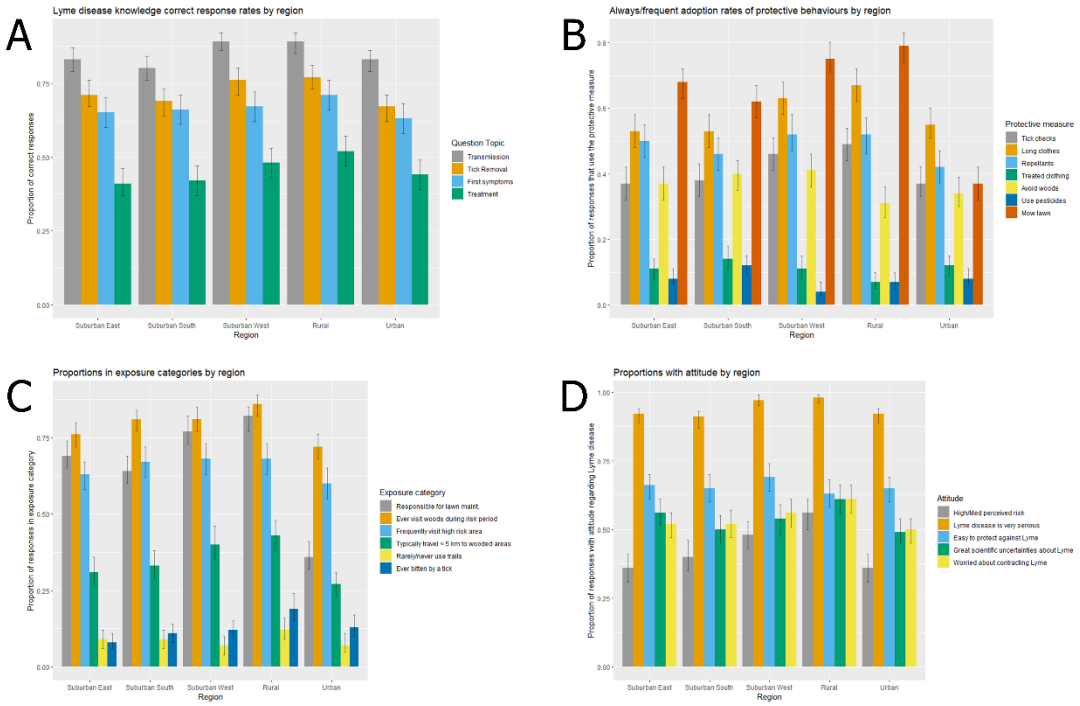

Figure 5.2 Responses to selected questions by region: (A) Lyme disease knowledge correct response rates, (B) always or frequent adoption rates of protective behaviours, (C) proportions in specified exposure categories, and (D) proportions expressing specified attitudes regarding Lyme disease. Bars represent the proportion of respondents in the respective region who provided the specified answer. Some depicted questions may have different population sizes due to non-applicability.

5.2.6.3 Adoption of personal protective measures

The most common personal protective measures adopted among Ottawa residents were regularly mowing the lawn on one's property (81%), wearing long clothing (66%), and performing tick checks after stays in wooded areas (60%) (Table 5.2). The citywide proportion of respondents with a high personal practice score (PS $\geq$ 5) was 14% and ranged from 11 to 17 percent across the geographic survey strata (Table 5.2, Table S5.5). 12% of respondents identified no protective measures that they frequently use, while 15% identified a single measure they adopt to protect against Lyme disease. A significantly higher proportion of Indigenous respondents identified practising a high adoption of protective behaviours (24%) compared to other population groups ($P<0.05$, see Table S5.5). Statistically significant differences existed between the proportions of White, Indigenous, and other racialized individuals that perform tick checks ($P<0.05$), as well as those that wear treated clothing, avoid woodlands between May and October, use pesticides on their property, and mow their lawn ($P<0.001$, see Table S5.2). Residents who lived in the western suburbs and rural areas of Ottawa also identified donning long clothing during or performing tick checks after activities in woodland areas more frequently than residents from other city regions (Figure 5.2B).

5.2.6.4 Exposure risk factors

Several exposure risk factors were common among respondents. Two-thirds of respondents claimed responsibility for maintaining their outdoor yard, and 22% had access to but no responsibility for yard space on their residential property. Only 415 respondents (21%) claimed they had never visited a wooded area between May and October of the survey year, with

seventeen percent stating that they visited one more than 25 times during the same period (Table 5.2). Residents living in Ottawa's urban core identified visiting wooded areas during the risk period less frequently than residents in other city regions (72%, Figure 5.2C). Of the primary reasons for visiting wooded areas during the May-October risk period, most respondents did so for recreation (1136, 56%), followed by dog walking (337, 17%).

Figure 5.3 depicts the sites selected by survey respondents as the woodland site they frequented most often between May and October during the previous year by distance travelled from their home postal code. These maps also display the degree of Lyme disease risk, or the estimated probability of blacklegged tick presence, in the area illustrated by the sources detailed above. In the preceding May to October risk period, 65% of respondents most frequently visited a wooded site that was high-risk for blacklegged tick exposure. Sites in western Ottawa appear to be more frequently visited by residents to whom these sites are local (Figure 5.3A) but also by Ottawa residents who travel further within the city to engage in their desired activity (Figures 5.3B-D). By comparison, fewer respondents remained in eastern or southern Ottawa or travelled a short distance for local woodland activity. Overall, 35% of respondents claimed to travel less than five kilometres for activities in wooded areas, while the average distance a respondent travelled to a frequently visited site was 18.6 kilometres. 2% of respondents travelled more than 125 kilometres from their home to the wooded location they visit most frequently, predominantly to sites north in the province of Quebec or west of Ottawa in Ontario (Figure 5.3E). There was a significant difference ($p<0.05$) in the average distance travelled between the 82% of respondents (1,314) who visited areas with high Lyme disease risk (15.4 kilometres) versus the remainder (288) who visited areas that represent low risk (33.9 kilometres). High exposure index (entering

higher-risk areas more frequently) occurred in a greater proportion of surveyed men compared to women, as well as a smaller proportion of respondents from other racialized groups compared to White and Indigenous individuals ($P<0.001$, see Table S5.1).

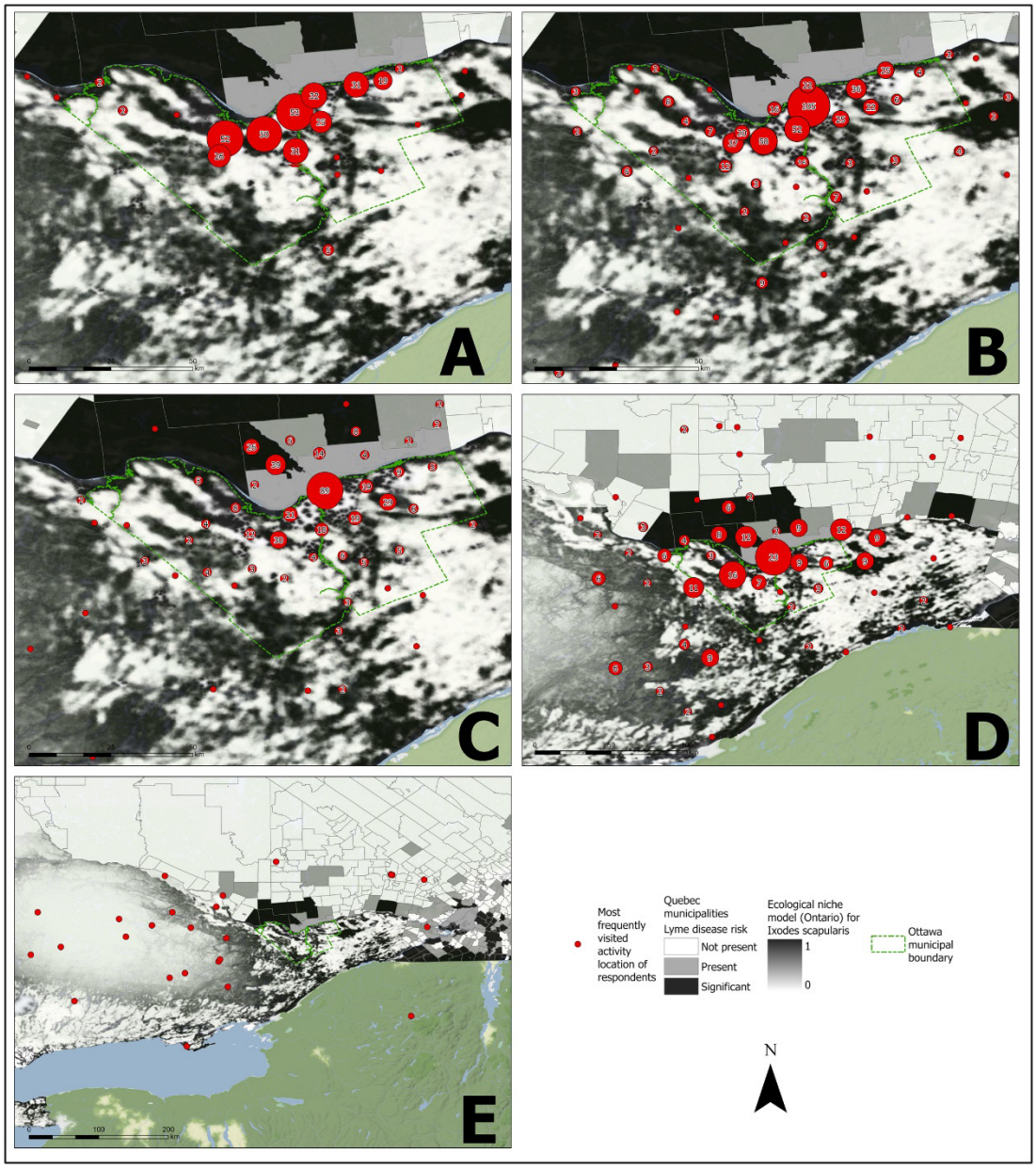

Figure 5.3 The most frequently visited locations for woodland activities by geodesic distance. Panels group locations by the shortest curvilinear path along the earth's surface between the respondent's home and the displayed activity location: (A) less than 2 kilometres, (B) 2 to 10 kilometres, (C) 10 to 30 kilometres, (D) 30 to 125 kilometres, and (E) greater than 125 kilometres. Numbers on maps and point sizes represent the number of respondents who identified locations within that area. The probability of blacklegged tick presence (Ontario) and estimated Lyme disease risk (Quebec) illustrate comparative Lyme disease risk between activity locations. Basemap by Stamen Design, under CC BY 4.0, with data by OpenStreetMap, under ODbL.

5.2.6.5 Statistical models

In the final Lyme disease knowledge model, the factor most strongly associated with a high knowledge level was residing on a property with personal responsibility for yard maintenance (Odds Ratio (OR) = 2.46, 95% Confidence Interval (CI): 1.75, 3.47; Table 5.3). Individuals 55 or older also exhibited a significant positive association (OR=1.92, 95%CI: 1.42, 2.62) compared to respondents in the youngest age group (18 to 34). High Lyme disease knowledge levels were 30% less likely in men than women (OR=0.69, 95%CI: 0.56, 0.86) and nearly 30% less likely among individuals belonging to non-Indigenous racialized groups compared to White respondents (OR=0.71, 95%CI: 0.53, 0.95). The likelihood of having a high knowledge level about Lyme disease was 71% greater for respondents with a high exposure index than those with a negligible risk of exposure (OR=1.71, 95%CI: 1.21, 2.41). Respondents who knew someone else that had been infected by Lyme disease were twice as likely to demonstrate a high level of Lyme disease knowledge (OR=2.03, 95%CI: 1.57, 2.63). Of all respondents, those who were unable to identify their own perceived risk of Lyme disease ("Don't Know") were nearly 80% less likely compared to those who identified their personal risk level as high (OR=0.23, 95%CI: 0.13, 0.38).

Table 5.3 Factors associated with high knowledge score (KS ≥ 3) regarding Lyme disease (n = 1,741)

Factors	Univariable			Multivariable		
	OR	**95% CI**	***P***	**OR**	**95% CI**	***P***
Region (ref: Suburban east)						
South	0.90	(0.67, 1.21)	0.5	0.90	(0.65, 1.24)	0.5
West	1.07	(0.79, 1.46)	0.7	0.82	(0.59, 1.16)	0.3
Rural	1.33	(0.97, 1.81)	0.08	0.99	(0.70, 1.40)	0.9
Urban	0.83	(0.62, 1.11)	0.2	1.09	(0.79, 1.52)	0.6
Age (ref: 18 to 34)						
35 to 54	1.63	(1.24, 2.14)	<0.001	1.39	(1.02, 1.89)	0.04
55 and older	2.46	(1.09, 3.21)	<0.001	1.92	(1.42, 2.62)	<0.001
Gender (ref: women)						
Men	0.77	(0.63, 0.93)	0.007	0.69	(0.56, 0.86)	<0.001
Other	0.61	(0.14, 2.60)	0.5	1.05	(0.21, 5.15)	0.9
Family income level (ref: $40k to $80k)						
< $40,000	0.63	(0.45, 0.87)	0.005			
$80,000 +	1.13	(0.91, 1.41)	0.3			
Education level (ref: High school or less)						
College	0.99	(0.70, 1.32)	0.8	0.79	(0.55, 1.12)	0.2
University and higher	1.05	(0.79, 1.38)	0.7	1.01	(0.74, 1.39)	0.9
Population group (ref: White)						
Indigenous persons	0.51	(0.29, 0.90)	0.02	0.62	(0.33, 1.15)	0.1
Other racialized persons	0.47	(0.36, 0.60)	<0.001	0.71	(0.53, 0.95)	0.02
Perceived risk level (ref: high)						
Medium	1.43	(1.01, 2.03)	0.05	1.35	(0.92, 1.97)	0.1
Low	0.99	(0.71, 1.37)	0.9	0.92	(0.64, 1.32)	0.7
None	0.46	(0.29, 0.73)	<0.001	0.57	(0.35, 0.95)	0.03
Don't know/Prefer not to answer	0.19	(0.12, 0.31)	<0.001	0.23	(0.13, 0.38)	<0.001
Outdoor yard (ref: none)						
Have yard, not responsible for maintenance	1.84	(1.32, 2.58)	<0.001	1.60	(1.12, 2.30)	0.01
Have yard, responsible for maintenance	3.26	(2.44, 4.39)	<0.001	2.46	(1.75, 3.47)	<0.001
Exposure index (ref: negligible)						
Low	1.25	(0.97, 1.59)	0.08	1.02	(0.78, 1.34)	0.9
Medium	1.69	(1.26, 2.28)	<0.001	1.41	(1.01, 1.98)	0.04
High	2.17	(1.61, 2.95)	<0.001	1.71	(1.21, 2.41)	0.002
Distance traveled to wooded areas (ref: <1 km)						
1 to 5 km	0.86	(0.60, 1.22)	0.4			
6 to 10 km	0.66	(0.45, 0.95)	0.03			
11 to 20 km	0.65	(0.44, 0.98)	0.04			
21+ km	1.13	(0.76, 1.65)	0.5			
No travel to wooded areas	0.51	(0.36, 0.72)	<0.001			
Duration of woodlands activities (ref: <1 hr)						
1 to 3 hours	1.47	(1.14, 1.88)	0.003			
4 to 8 hours	0.75	(0.52, 1.08)	0.1			
9 to 24 hours	1.52	(0.65, 3.82)	0.3			
> 1 day	1.47	(0.81, 2.79)	0.2			
No travel to wooded areas	0.73	(0.55, 0.98)	0.03			
Use cleared paths/trails in woodland areas (ref: always)						
Frequently	1.14	(0.89, 1.47)	0.3			
Rarely	0.79	(0.52, 1.21)	0.3			
Sometimes (not because of Lyme disease)	0.77	(0.51, 1.15)	0.2			
Never	1.01	(0.39, 2.81)	0.9			
No travel to wooded areas	0.63	(0.47. 0.83)	0.001			
Currently own a dog	1.22	(0.98, 1.52)	0.07			
Ever had Lyme disease (ref: no)						
Yes	0.65	(0.40, 1.06)	0.09			
Don't know	1.07	(0.62, 1.86)	0.8			
Know someone who has had Lyme disease	2.65	(2.10, 3.38)	<0.001	2.03	(1.57, 2.63)	<0.001
Ever bitten by a tick	1.42	(1.06, 1.92)	0.02			
Primary reason in wooded areas: work	0.63	(0.34, 1.15)	0.1	0.59	(0.31, 1.13)	0.1
Primary reason in wooded areas: fitness/recreation	1.37	(1.13, 1.67)	0.001			
Primary reason in wooded areas: birdwatching	0.73	(0.51, 1.04)	0.08	0.60	(0.40, 0.88)	0.01
Primary reason in wooded areas: dog walking	1.03	(0.80, 1.33)	0.8			
Primary reason in wooded areas: camping	1.19	(0.80, 1.79)	0.4			
Primary reason in wooded areas: hunting	0.49	(0.18, 1.27)	0.1	0.36	(0.12, 1.00)	0.05
Primary reason in wooded areas: cottage	1.35	(0.95, 1.94)	0.1			

Respondents who answered "I prefer not to answer" to any of the explanatory variables were excluded from multivariable analysis. Gender, age, education level, and region were forced into the model as potential confounding variables.

Table 5.4 presents the association between different factors and high personal protective practices scores. In the final model, the factors most strongly associated with high adoption were visiting wooded areas most frequently for work (OR=2.78, 95%CI: 1.31, 5.67) and having an outdoor yard, with or without responsibility for its maintenance (OR=2.59, 95%CI: 1.42, 4.98; OR=2.53, 95%CI: 1.43, 4.78). Respondents who reported previous infection with Lyme disease were more than twice as likely to adopt five or more protective practices (OR=2.22, 95%CI: 1.19, 4.00). Respondents from non-Indigenous racialized groups were 90% more likely to demonstrate greater adoption than White Ottawa respondents (OR=1.92, 95%CI: 1.31, 2.79). Respondents who were assigned a high exposure risk index (OR=0.50, 95%CI: 0.30, 0.80), believed themselves at low risk of infection with Lyme disease (OR=0.38, 95%CI: 0.25, 0.60), or did not know whether they were at risk (OR=0.25, 95%CI: 0.11, 0.53) were less likely to adopt protective practices. Results from our sensitivity analysis, wherein property-level measures were removed from the total possible protective practices score, were similar to our primary analysis overall (see Table S5.3). In this version of the analysis, the major difference was a loss of significance for having a yard and the responsibility for its maintenance. However, having a yard and no maintenance obligations was still associated with more than two times the likelihood (OR=2.09; 95%CI: 1.27, 3.54; Table S5.3) of a respondent demonstrating a high adoption of protective practices compared to having no yard access.

Multicollinearity was not detected between levels of any independent variables in either the knowledge or the personal protective practices model.

Table 5.4 Factors associated with high Lyme disease protective practices score (PS ≥ 5) (n = 1,741)

Factors	Univariable			Multivariable		
	OR	95% CI	*P*	OR	95% CI	*P*
Region (ref: Suburban east)						
South	1.06	(0.70, 1.61)	0.8	1.01	(0.66, 1.57)	0.9
West	1.02	(0.66, 1.57)	0.9	1.00	(0.64, 1.57)	0.9
Rural	0.89	(0.58, 1.38)	0.6	0.85	(0.53, 1.36)	0.5
Urban	0.66	(0.42, 1.02)	0.06	0.73	(0.45, 1.18)	0.2
Age (ref: 18 to 34)						
35 to 54	1.09	(0.74, 1.62)	0.7	1.13	(0.74, 1.75)	0.6
55 and older	0.84	(0.58, 1.24)	0.4	1.04	(0.67, 1.62)	0.9
Gender (ref: women)						
Men	1.05	(0.79, 1.38)	0.7	0.98	(0.73, 1.32)	0.9
Other	0.94	(0.05, 5.36)	0.9	0.66	(0.03, 4.62)	0.7
Family income level (ref: $40k to $80k)						
< $40,000	0.98	(0.60, 1.57)	0.9			
$80,000 +	1.03	(0.75, 1.42)	0.9			
Education level (ref: High school or less)						
College	0.81	(0.52, 1.27)	0.4	0.75	(0.47, 1.21)	0.2
University and higher	0.83	(0.57, 1.23)	0.3	0.72	(0.48, 1.11)	0.1
Population group (ref: White)						
Indigenous persons	2.36	(1.16, 4.48)	0.01	1.59	(0.71, 3.31)	0.2
Other racialized persons	1.78	(1.28, 2.47)	<0.001	1.92	(1.31, 2.79)	<0.001
Perceived risk level (ref: high)						
Medium	0.58	(0.39, 0.87)	0.01	0.62	(0.40, 0.95)	0.03
Low	0.33	(0.22, 0.50)	<0.001	0.38	(0.25, 0.60)	<0.001
None	0.50	(0.27, 0.89)	0.02	0.59	(0.30, 1.11)	0.1
Don't know	0.21	(0.09, 0.44)	<0.001	0.25	(0.11, 0.53)	<0.001
Outdoor yard (ref: none)						
Have yard, not responsible for maintenance	2.49	(1.41, 4.67)	0.003	2.59	(1.42, 4.98)	0.003
Have yard, responsible for maintenance	2.46	(1.47, 4.44)	0.001	2.53	(1.43, 4.78)	0.003
Exposure index (ref: negligible)						
Low	0.91	(0.63, 1.29)	0.6	0.72	(0.49, 1.07)	0.1
Medium	1.02	(0.67, 1.52)	0.9	0.71	(0.45, 1.12)	0.1
High	0.83	(0.53, 1.25)	0.4	0.50	(0.30, 0.80)	0.005
Distance traveled to wooded areas (ref: <1 km)						
1 to 5 km	0.94	(0.59, 1.52)	0.8			
6 to 10 km	1.06	(0.65, 1.75)	0.8			
11 to 20 km	1.04	(0.61, 1.79)	0.9			
21+ km	0.71	(0.42, 1.22)	0.2			
No travel to wooded areas	0.57	(0.34, 0.97)	0.04			
Duration of woodlands activities (ref: <1 hr)						
1 to 3 hours	0.83	(0.59, 1.17)	0.3			
4 to 8 hours	1.12	(0.68, 1.80)	0.7			
9 to 24 hours	0.76	(0.18, 2.28)	0.7			
> 1 day	0.59	(0.20, 1.41)	0.3			
No travel to wooded areas	0.54	(0.34, 0.84)	0.007			
Use cleared paths/trails in woodland areas (ref: always)						
Frequently	0.76	(0.54, 1.07)	0.1			
Rarely	1.12	(0.63, 1.91)	0.7			
Sometimes (not because of Lyme disease)	0.77	(0.42, 1.34)	0.4			
Never	0.62	(0.10, 2.26)	0.5			
No travel to wooded areas	0.48	(0.30, 0.74)	0.001			
Currently own a dog	1.25	(0.92, 1.68)	0.1			
Ever had Lyme disease (ref: no)						
Yes	3.02	(1.71, 5.13)	<0.001	2.22	(1.19, 4.00)	0.009

Don't know	1.51	(0.71, 2.91)	0.3	1.31	(0.60, 2.64)	0.5
Know someone who has had Lyme disease	1.33	(0.98, 1.79)	0.06			
Ever bitten by a tick	1.84	(1.27, 2.62)	0.001	1.62	(1.07, 2.43)	0.02
High Lyme disease knowledge score	0.91	(0.69, 1.20)	0.5			
Primary reason in wooded areas: work	3.49	(1.80, 6.52)	<0.001	2.78	(1.31, 5.67)	0.006
Primary reason in wooded areas: fitness/recreation	1.38	(1.04, 1.84)	0.03	1.58	(1.14, 2.19)	0.006
Primary reason in wooded areas: birdwatching	1.51	(0.93, 2.37)	0.08			
Primary reason in wooded areas: dog walking	1.05	(0.73, 1.50)	0.8			
Primary reason in wooded areas: camping	1.47	(0.87, 2.39)	0.1			
Primary reason in wooded areas: hunting	1.38	(0.32, 4.28)	0.6			
Primary reason in wooded areas: cottage	1.47	(0.92, 2.27)	0.09	1.80	(1.10, 2.88)	0.02

Respondents who answered "I prefer not to answer" to any of the explanatory variables were excluded from multivariable analysis. Gender, age, education level, and region were forced into the model as potential confounding variables.

5.2.7 Discussion

Our survey of residents in a large Canadian municipality sheds light on the level of knowledge and adoption of preventive behaviours concerning Lyme disease in a Canadian region with rapid blacklegged tick emergence. Respondents generally perceived Lyme as a serious disease, and roughly two out of every five individuals believed themselves at high or medium risk during the previous spring and summer. Just over half of respondents worried about contracting Lyme disease regardless of personal risk perception. Our results show that while most Ottawa residents recognized the need to protect themselves against Lyme disease, they were less familiar with the specifics of its transmission, presentation, and treatment. Most surveyed residents identified that the pathogen causing Lyme disease was transmitted exclusively by a bite from an infected tick, consistent with 2017 municipal statistics reported from Rapid Risk Factor Surveillance System surveys conducted by Ottawa Public Health [5]. However, in our results, the overall knowledge demonstrated was low, with 60% of surveyed individuals correctly answering at least three of the four knowledge questions. For population subgroups, a higher knowledge score was significantly more likely among respondents who identified as women, older than 55, or White.

There were notable variations in the level of Lyme disease knowledge among Ottawa residents. Among geographic subgroups, the proportions of respondents who provided the correct answer to each of the knowledge questions were consistently highest in the suburban west and rural regions. Our results demonstrate a similar geographic pattern concerning those who felt at high or medium risk of contracting Lyme disease. Community awareness of the peridomestic presence and abundance of blacklegged ticks in these areas of Ottawa may explain this geographic difference in personal perception of risk and overall Lyme disease knowledge. Prior studies have shown that the highest density of host-seeking ticks [7,8] and the highest incidence of locally-acquired Lyme disease [31] occur within these same regions of the city. However, our final model of high Lyme disease knowledge did not find a significant association with the city region where the respondent lives, suggesting personal factors might inform Lyme disease knowledge more than location of residence.

Where the threat of tick-borne disease transmission exists, understanding the relationship between population knowledge, exposure potential, and adoption of personal protection is essential to assess educational outreach needs. Three interesting dynamics stood out in our multivariable analyses of composite scores for knowledge and personal practices. First, strong and significant associations existed for the composite scores of knowledge and practices with access to and responsibility for maintaining an outdoor yard. A widely accepted premise in areas where Lyme disease vectors and pathogens are highly endemic, such as the northeast United States, is that a significant proportion of tick exposures resulting in Lyme disease infection occur on residential properties [49]. In contrast, our results indicated that just over 40% of Ottawa

residents believe that, locally, it is possible to contract Lyme disease in residential areas. Many Ottawa Lyme disease cases are also attributed to tick bite encounters outside the patient's home neighbourhood [5,31]. Even so, Ottawa residents with access to or responsibility for an outdoor yard were more than twice as likely to demonstrate high protective behaviour adoption than those without such outdoor space. Even when property-level protections were removed as a component of the protective practices score in our sensitivity analysis, access to a yard without the need to maintain it retained its significant association with high practices adoption compared to respondents with no yard access. The greater extent of protective measures practiced by residents with access to outdoor yards seems discordant with the perception of residential risk local to Ottawa. This may have multiple causes. One explanation could be that residents with lawns avail themselves of more resources that increase personal awareness of ticks and tick-borne diseases. They may believe their actions consistently reduce or eliminate the backyard risk of tick encounters. Another possibility is that the same respondents believe the local risk of Lyme disease is not high and mow their lawns as a precaution but adopt other measures during recreation as their primary protection method. The adoption rates for individual practices among our sample all fall within the highly variable ranges observed in other studies on preventive and protective practices conducted in Lyme endemic areas [14,18,50–52][14,18,50–52]. Even with a high variability in adoption among the individual measures, our results highlight a clear difference in the likelihood of high knowledge and adoption of protective practices regarding Lyme disease rooted in outdoor yard access. Public health communication may require different strategies for residents without outdoor yards.

Secondly, our study demonstrated significant differences between population sub-groups in the composite scores for knowledge and personal practices adoption. Controlling for other factors, respondents who belonged to a non-Indigenous racialized population group were one-third less likely than White respondents to demonstrate a high knowledge of Lyme disease yet were two-thirds more likely to practise a high adoption of protective behaviours. Despite lower awareness of specific details of Lyme disease transmission and treatment, members of non-Indigenous racialized groups appear to adopt recommended protective behaviours readily. This apparent dissociation between the level of Lyme disease knowledge and personal protection is interesting, as both groups contained a comparable proportion of respondents who believed themselves to be at elevated personal risk (see Table S5.1). While a greater proportion of White respondents identified always or frequently performing tick checks after activities in wooded areas, by contrast, nearly half of non-Indigenous racialized respondents declared avoiding woodlands entirely (see Table S5.2). Similarly, more than twice the proportion of non-Indigenous racialized respondents indicated a high frequency of using insecticide-treated clothing and pesticides on personal property. Further research into the motivation driving individuals to adopt one or more protective practices, particularly when using one measure at the exclusion of others, could help clarify the dynamics of these personal choices.

We might consider the third dynamic from this analysis as a "false sense of security" gap, characterized by the opposing direction of association with knowledge and personal practices among respondents classified as having a high exposure index. When we adjusted for other factors, these respondents were more likely to demonstrate high Lyme disease knowledge and

half as likely to have high levels of adoption of protective practices. We might dismiss this conflicted behaviour as an error in individuals' risk perception. However, the high exposure index category had the largest proportion of individuals who identified their perceived risk level as high or medium (see Table S5.4). It follows that residents who engage in activities contributing to higher exposure risk for Lyme disease do not lack awareness of the local environmental hazard. Instead, these individuals may have been lulled into inaction over time by non-events – that is, they have not previously had a tick encounter or have experienced tick encounters with such relative infrequency that they dismiss additional measures as unnecessary. Another explanation could be that these individuals choose and rely on fewer protective measures at the exclusion of others, with the belief that the actions they take afford them the best balance of safety and personal comfort. Further qualitative research would help identify the processes motivating individuals with high exposure risk to adopt fewer protective measures, including the decisions that lead to adopting or disusing particular measures.

This relationship among respondents with a high exposure index holds particular interest in informing local public health messaging. Our results suggest potential differences in how Ottawa residents translate their perception of risk at home compared to when they engage in outdoor activities elsewhere. In general, a large proportion of respondents located outside the urban core mow private lawns as a form of Lyme disease prevention. Locally, where individuals have responsibility for a property, lawncare and tick exposure risk thus appear to be well-connected in the public consciousness. In contrast, the proportion of respondents who perform tick checks after, or wear long clothing during, activities in woodlands was greater among respondents who

live in the city's western suburbs or rural areas. As noted above [8,31], these locations represent the municipal region's most established Lyme disease risk areas. That is, where blacklegged ticks are commonly understood to be abundant, residents' usage rates of personal protective measures (e.g., tick checks, long clothing) are higher. Yet sixty-five percent of survey respondents in our sample frequently visited a site determined to be high-risk based on the probability of established blacklegged tick populations. Moreover, many respondents specified visiting wooded areas in Ottawa's western Greenbelt – either by crossing the city or merely their backyard. Our models indicate no regional differences exist in either high knowledge or adoption rates of protective practices overall. However, these apparent patterns of travel within the city for activities combined with differences in the adoption of personal protection methods suggest Lyme disease risk may not remain in focus when individuals stray outside their own neighbourhood.

The study design has some limitations which may impact its generalizability. As with any survey, self-selected participation carries the risk that responses may not be broadly representative of the sampled population. Administrators of the survey recruited respondents through a web panel. While they applied recruitment quotas to ensure the sample was representative of national population demographics, the panel selection slightly over-represented older, more educated individuals who may be more likely to enrol and participate. However, internet-administered surveys have provided similar estimates of Lyme disease knowledge and adaptation behaviours compared to other methods [53][53]. Respondents were asked in the fall to recall their activities and actions up to six months prior and cumulatively over this period. As such, the categorical choices may misrepresent the actual frequency and circumstance of

protective behaviours practiced by individuals. We did not ask respondents to identify whether they preferred one measure at the exclusion of all others, which may contribute to an underestimation of associations with strong preventive behaviours [14]. We also can not dismiss the possibility of reverse causality concerning self-perceived risk. As the most practised method of Lyme disease prevention identified in our survey was lawn maintenance, respondents who identified always or frequently applying this measure may believe their likelihood of encountering ticks is low altogether. Given the cross-sectional design, our aim was not to determine the decision processes and conditions driving the selection of specific preventive measures. Prospective research on the use of these methods, whether they are constant or wax and wane throughout a risk season, and the combinations or exclusivity of behaviours, will be necessary to further develop personal and public health strategies - especially in areas where Lyme disease risk is still becoming established. Our results are also partially dependent on our partitioning of Ottawa into the five defined regions. The modifiable areal unit problem of statistical inference should be kept in mind when interpreting any results comparing observations between imposed geographic zones [54–56][54–56]. Though we aimed to follow accepted guidelines in the definition of urbanicity, we recognize that these results might differ if we had made different choices in these zones' definitions. Lastly, we conducted this survey during the COVID-19 pandemic when individuals often had to alter their behaviours. During the period from mid-March until June of 2020, Ottawa Public Health asked residents to limit non-essential outings and businesses remained closed across the province of Ontario. Restrictions enacted by the Ottawa municipal government and National Capital Commission, the agency responsible for federal lands that include Ottawa's wooded Greenbelt, also included closures of parks for group activities and vehicle access to parking at Greenbelt trailheads. This further limited access to

some outdoor spaces from March until July. As a result, people may have visited woodland areas more or less than during the same time in other years, depending on personal circumstances and periodic restrictions that may have been in place.

5.2.8 Conclusions

The results of this study highlight the interplay between people's knowledge, patterns of awareness, and levels of vigilance in protection regarding Lyme disease. With insight into these patterns, public health officials might tailor public health messaging to different communities. Timely identification of gaps between the perceived and actual local risk posed by establishing populations of blacklegged ticks is crucial. Outreach that emphasizes the increasing risk in various local outdoor settings – in backyards and beyond – might temper the false sense of security some residents may feel. Enhanced messaging might also present opportunities to emphasize the preventive benefit of adopting multiple complementary protective behaviours. Future analyses should examine the types of activity, locations, and attitudes contributing to reduced personal vigilance in preventing infection with tick-borne pathogens.

5.2.9 Acknowledgements

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assisted with the technical development of the web-administered survey and conducted participant recruitment.

5.2.10 Supporting Information

Table S5.1 Proportion of Lyme disease knowledge, risk factors, attitudes, and practices by select sample subgroups

	Gender n (%)			Age group n (%)			Population Group[1] n (%)			Total %
	Men	Women	Other	18 to 34	35 to 54	55+	White	Indigenous	Other	
Total	995	1015	8	381	646	991	1592	55	349	2018
High Lyme disease knowledge score (KS ≥ 3)	562 (56)	645 (64)*	4 (50)	166 (44)**	375 (58)	670 (68)**	1018 (64)**	25 (45)	154 (44)	1211 (60)
Perceived risk (high or medium)[1]	387 (42)	399 (44)	3 (43)	145 (44)	280 (48)*	364 (39)*	618 (42)	32 (64)*	132 (44)	789 (43)
High personal practices score (PS ≥ 5)	134 (13)	140 (14)	1 (13)	53 (14)	98 (15)	124 (13)	194 (12)*	13 (24)*	60 (17)	275 (14)
Seek and remove ticks[1]	415 (57)	416 (64)*	2 (33)*	157 (58)	281 (60)	395 (61)	685 (61)	28 (70)*	109 (51)*	833 (60)
Wear long clothing[1]	560 (63)*	606 (69)	5 (71)	206 (61)	369 (63)	596 (70)*	925 (66)	32 (68)	200 (67)	1171 (66)
Use repellents[1]	470 (52)	499 (54)	3 (43)	164 (48)	332 (56)	476 (53)	779 (53)	27 (55)	159 (52)	972 (53)
Wear treated clothing[1]	121 (14)	101 (12)	0 (0)	56 (17)*	77 (14)	89 (11)*	139 (10)	11 (23)**	68 (24)**	222 (13)
Avoid woodlands[1]	337 (38)	397 (45)*	3 (43)	126 (38)	231 (39)	380 (45)*	547 (39)	24 (50)**	157 (51)**	737 (41)
Use pesticides[1]	98 (12)	65 (8)*	0 (0)*	45 (16)**	67 (13)	51 (6)**	97 (8)	12 (29)**	49 (18)**	163 (10)
Mow lawn[1]	640 (79)	637 (84)*	4 (67)*	151 (59)**	443 (83)	687 (87)	1061 (84)	28 (68)**	180 (71)**	1281 (81)
Exposure index (high or medium)	322 (32)**	242 (24)	1 (14)**	104 (27)	198 (31)	263 (27)	480 (30)	17 (31)	62 (18)**	565 (28)
Walk on trails/paths during activities in wooded areas[1]	660 (67)	628 (62)	6 (75)	227 (60)	446 (69)*	621 (63)	1063 (67)	36 (65)	185 (53)**	1294 (64)
Own a dog[1]	277 (28)	234 (23)	3 (38)*	105 (28)*	184 (28)*	225 (23)	425 (27)	30 (55)**	58 (17)**	514 (25)
Had Lyme disease[1]	43 (4)	31 (3)	0 (0)	22 (6)	28 (5)	24 (2)*	49 (3)	8 (15)**	16 (5)**	74 (4)
Know someone who has had Lyme disease	229 (23)	299 (29)**	3 (38)**	70 (19)**	156 (24)	305 (31)**	456 (29)	18 (33)**	53 (15)**	531 (26)
Ever bitten by a tick	153 (15)**	95 (9)	3 (38)**	39 (2)	82 (13)	130 (13)	203 (13)	15 (27)**	26 (8)**	251 (12)

[1] *Respondents who answered "Don't know", "I prefer not to answer", or "Does not apply to my situation" were excluded.*

* *Significant ($p < 0.05$) difference when compared to other genders, age, or population groups (Pearson Chi-square statistic, or Fisher's exact test where appropriate)*

** *Significant ($p < 0.001$) difference when compared to other genders, age, or population groups (Pearson Chi-square statistic, or Fisher's exact test where appropriate*

Table S5.2 Personal protective measure responses by population group

	White[1]					Indigenous persons[1]					Other racialized persons[1]				
	Always	Frequently	Rarely	Never / Does not apply	Sometimes*	Always	Frequently	Rarely	Never / Does not apply	Sometimes*	Always	Frequently	Rarely	Never / Does not apply	Sometimes*
Total (%)	n = 1592					n = 55					n = 349				
Seek and remove ticks after a stay in a forested area	360 (23)	325 (20)	252 (16)	602 (38)	45 (3)	16 (29)	12 (22)	6 (11)	17 (31)	3 (5)	57 (16)	52 (15)	51 (15)	169 (48)	15 (4)
Wear long clothing that covers the legs	390 (24)	535 (34)	269 (17)	294 (18)	98 (6)	14 (25)	18 (33)	7 (13)	11 (20)	5 (9)	92 (26)	108 (31)	51 (15)	70 (20)	25 (7)
Use insect repellants with DEET or Icaridin	289 (18)	490 (31)	359 (23)	306 (19)	142 (9)	14 (25)	13 (24)	10 (18)	10 (18)	7 (13)	71 (20)	88 (25)	63 (18)	86 (25)	38 (11)
Wear clothing treated with insecticide	55 (3)	84 (5)	196 (12)	1222 (77)	27 (2)	6 (11)	5 (9)	8 (15)	32 (58)	4 (7)	30 (9)	38 (11)	44 (13)	223 (64)	10 (3)
Avoid woodlands during the spring-to-fall risk period	150 (9)	397 (25)	422 (27)	537 (34)	78 (5)	10 (18)	14 (25)	12 (22)	13 (24)	6 (11)	60 (17)	97 (28)	76 (22)	84 (24)	27 (8)
Put pesticides on my property	33 (2)	64 (4)	175 (11)	959 (60)	57 (4)	5 (9)	7 (13)	5 (9)	34 (62)	3 (5)	21 (6)	28 (8)	56 (16)	227 (65)	13 (4)
Mow the lawn regularly on my property	681 (43)	380 (24)	57 (4)	381 (24)	85 (5)	19 (35)	9 (16)	7 (13)	15 (27)	3 (5)	83 (24)	97 (28)	31 (9)	109 (31)	23 (7)

* Sometimes indicates "Sometimes I apply this measure, but not to protect myself from Lyme disease".

[1] "I prefer not to answer" responses are not presented under population group responses.

Table S5.3 Results from sensitivity analysis for factors associated with high Lyme disease protective practices score (PS ≥ 4) on a scale of 5 total measures (n = 1,741)

Factors	Multivariable		
	OR	**95% CI**	***P***
Region (ref: Suburban east)			
South	0.89	(0.58, 1.38)	0.6
West	1.10	(0.71, 1.70)	0.7
Rural	0.82	(0.51, 1.29)	0.4
Urban	0.91	(0.58, 1.40)	0.7
Age (ref: 18 to 34)			
35 to 54	1.33	(0.88, 2.03)	0.2
55 and older	1.25	(0.83, 1.92)	0.3
Gender (ref: women)			
Men	0.95	(0.71, 1.26)	0.7
Other	0.69	(0.03, 4.55)	0.7
Education level (ref: High school or less)			
College	0.76	(0.49, 1.20)	0.2
University and higher	0.69	(0.47, 1.04)	0.07
Population group (ref: white)			
Indigenous persons	1.39	(0.63, 2.87)	0.4
Other racialized persons	1.87	(1.30, 2.68)	<0.001
Perceived risk level (ref: high)			
Medium	0.58	(0.38, 0.88)	0.01
Low	0.35	(0.23, 0.53)	<0.001
None	0.48	(0.25, 0.89)	0.02
Don’t know	0.34	(0.17, 0.65)	0.002
Outdoor yard (ref: none)			
Have yard, not responsible for maintenance	2.09	(1.27, 3.54)	0.005
Have yard, responsible for maintenance	1.34	(0.82, 2.24)	0.3
Exposure index (ref: negligible)			
Low	0.91	(0.63, 1.32)	0.6
Medium	0.79	(0.50, 1.21)	0.3
High	0.54	(0.33, 0.85)	0.01
Ever had Lyme disease (ref: no)			
Yes	2.37	(1.30, 4.19)	0.004
Don’t know	1.52	(0.74, 2.93)	0.2
Know someone who has had Lyme disease	1.38	(1.01, 1.87)	0.04
Ever bitten by a tick			
Primary reason in wooded areas: work	2.52	(1.19, 5.11)	0.01
Primary reason in wooded areas: fitness/recreation	1.53	(1.12, 2.10)	0.007
Primary reason in wooded areas: cottage	1.60	(0.98, 2.54)	0.05

Respondents who answered “I prefer not to answer” to any of the explanatory variables were excluded from multivariable analysis.

Gender, age, education level, and region were forced into the model as potential confounding variables.

Table S5.4 Ottawa city region, risk perception, and past tick bite status by exposure index level

			Exposure Index			
		Total	Negligible	Low	Medium	High
Total n (%)		2018	1018	435	267	298
Region[1]	Suburban East	419	233 (56)**	82 (20)	58 (14)	46 (11)
	Suburban South	405	203 (50)	91 (22)	57 (14)	54 (13)
	Suburban West	381	177 (46)	85 (22)	38 (10)	81 (21)**
	Rural	380	162 (43)	92 (24)	51 (13)	75 (20)**
	Urban	433	243 (56)**	85 (20)	63 (15)	42 (10)
Perceived risk[1,2]	None	155	130 (84)**	19 (12)**	6 (4)	0 (0)
	Low	893	454 (51)	218 (24)	122 (14)	99 (11)
	Medium	576	205 (36)	136 (24)	106 (18)	129 (22)**
	High	213	93 (44)	42 (20)	26 (12)	52 (24)**
Ever bitten by a tick[1,2]	Yes	251	71 (28)	57 (23)	47 (19)	76 (30)**
	No	1763	945 (54)**	377 (21)	219 (12)	222 (13)

[1] *Proportions are calculated for row totals.*
[2] *Respondents who answered "Don't know / not sure" or "I prefer not to answer" were excluded.*
[*] *Significant ($p < 0.05$) difference when compared to other genders, age, or population groups (Pearson Chi-square statistic, or Fisher's exact test where appropriate)*
[**] *Significant ($p < 0.001$) difference when compared to other genders, age, or population groups (Pearson Chi-square statistic, or Fisher's exact test where appropriate)*

Table S5.5 Knowledge and personal practice measures scores[1] by population groups and regions

		Knowledge score					Personal practice score							
	Total n (%)	0	1	2	3	4	0	1	2	3	4	5	6	7
White	1592	45 (3)	173 (11)	356 (22)	489 (31)	529 (33)	164(10)	244 (15)	329 (21)	367 (23)	294 (18)	129 (8)	46 (3)	19 (1)
Indigenous persons	55	8 (15)	13 (24)	9 (16)	12 (22)	13 (24)	11 (20)	6 (11)	5 (9)	12 (22)	8 (15)	6 (11)	1 (2)	6 (11)
Other racialized persons	349	43 (12)	59 (17)	93 (27)	94 (27)	60 (17)	66 (19)	46 (13)	70 (20)	53 (15)	54 (15)	21 (6)	17 (5)	22 (6)
Suburban East	419	21 (5)	49 (12)	99 (24)	153 (37)	97 (23)	54 (13)	69 (16)	79 (19)	86 (21)	71 (17)	34 (8)	15 (4)	11 (3)
Suburban South	405	25 (6)	57 (14)	95 (23)	117 (29)	111 (27)	60 (15)	55 (14)	80 (20)	84 (21)	66 (16)	33 (8)	15 (4)	12 (3)
Suburban West	381	14 (4)	37 (10)	91 (24)	108 (28)	131 (34)	27 (7)	46 (12)	80 (21)	91 (24)	74 (19)	42 (11)	14 (4)	7 (2)
Rural	380	12 (3)	34 (9)	79 (21)	113 (30)	142 (37)	24 (6)	45 (12)	77 (20)	94 (25)	94 (25)	31 (8)	10 (3)	5 (1)
Urban	433	25 (6)	71 (16)	98 (23)	109 (25)	130 (30)	81 (19)	85 (20)	90 (21)	78 (18)	53 (12)	21 (5)	13 (3)	12 (3)

[1] Scores represent the number of protective measures respondents indicated they use “Always” or “Frequently”.

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Chapter 6

Peridomestic Lyme disease risk in Ottawa neighbourhoods

6.1 Article preface

In this chapter, I aimed to quantify differences in Lyme disease hazard, or environmental risk, between residential, woodlands, and residential-woodland interface ('interface') zones of Ottawa neighbourhoods with established tick populations. I used active surveillance data from tick drags and small mammal trapping efforts, as well as observations of deer foraging activity to analyze neighbourhood and zonal patterns of tick abundance for the studied area. I used ecological observations recorded at each sampling location to control for between-site differences in aspects of the microhabitat that are associated with tick survival, allowing me to isolate the zonal effects that were my primary interest. This analysis is related to Chapter 4, in that I analyze local ecotonal associations with Lyme disease hazard across several of the neighbourhoods identified as exhibiting the highest local Lyme disease incidence in the landscape analysis presented in that chapter.

6.1.1 Author contributions

Dr. Roman McKay, Dr. Benoit Talbot, Dr. Manisha Kulkarni, and I designed the study, selected neighbourhoods and identified sampling zones. Dr. McKay and I tabulated data and processed and organized the data for analysis. I designed and performed all statistical analyses, with guidance from my supervisor, Dr. Kulkarni. I wrote the first version of the manuscript, with major contributions from Dr. Kulkarni and substantive revision by Dr. Anders Knudby, Dr.

Patrick Leighton, Dr. Benoit Talbot, Dr. Roman McKay, Dr. Tim Ramsay, Dr. Justine Blanford, and Dr. Nicholas Ogden.

6.1.2 Article citation

Logan JJ, Knudby A, Leighton, PA, *et al. Ixodes scapularis* density and *Borrelia burgdorferi* prevalence along a residential-woodland gradient in a region of emerging Lyme disease risk. *Sci Rep* **14**, 13107 (2024). https://doi.org/10.1038/s41598-024-64085-6.

6.2 Article content

6.2.1 Title

Ixodes scapularis density and *Borrelia burgdorferi* prevalence along a residential-woodland gradient in a region of emerging Lyme disease risk

6.2.2 Authors

James J. Logan

School of Epidemiology and Public Health, University of Ottawa, Ottawa, Ontario, Canada

Anders Knudby

Department of Geography, Environment & Geomatics, University of Ottawa, Ottawa, Ontario, Canada

Patrick A. Leighton

Department of Pathology and Microbiology, Faculty of Veterinary Medicine, Université de Montréal, Saint-Hyacinthe, Québec, Canada

Benoit Talbot
School of Epidemiology and Public Health, University of Ottawa, Ottawa, Ontario, Canada

Roman McKay
School of Epidemiology and Public Health, University of Ottawa, Ottawa, Ontario, Canada

Tim Ramsay
School of Epidemiology and Public Health, University of Ottawa, Ottawa, Ontario, Canada
Ottawa Hospital Research Institute, University of Ottawa, Ottawa, Ontario, Canada

Justine I. Blanford
Department of Earth Observation Science, Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, Netherlands

Nicholas H. Ogden
Public Health Risk Sciences Division, National Microbiology Laboratory, Public Health Agency of Canada, Saint-Hyacinthe, Québec, Canada

Manisha A. Kulkarni
School of Epidemiology and Public Health, University of Ottawa, Ottawa, Ontario, Canada

6.2.3 Abstract

The environmental risk of Lyme disease, defined by the density of *Ixodes scapularis* ticks and their prevalence of *Borrelia burgdorferi* infection, is increasing across the Ottawa, Ontario region, making this a unique location to explore the factors associated with environmental risk along a residential-woodland gradient. In this study, we collected *I. scapularis* ticks and trapped *Peromyscus spp.* mice, tested both for tick-borne pathogens, and monitored the intensity of foraging activity by deer in residential, woodland, and residential-woodland interface zones of four neighbourhoods. We constructed mixed-effect models to test for site-specific characteristics associated with densities of questing nymphal and adult ticks and the infection prevalence of nymphal and adult ticks. Compared to residential zones, we found a strong increasing gradient in tick density from interface to woodland zones, with 4 and 15 times as many nymphal ticks, respectively. Infection prevalence of nymphs and adults together was 15 to 24 times greater in non-residential zone habitats. Ecological site characteristics, including soil moisture, leaf litter depth, and understory density, were associated with variations in nymphal density and their infection prevalence. Our results suggest that high environmental risk bordering residential areas poses a concern for human-tick encounters, highlighting the need for targeted disease prevention.

6.2.4 Introduction

Lyme disease, a tick-borne illness in humans, which in North America is caused by infection with *Borrelia burgdorferi* sensu stricto (s.s.), is the most common vector-borne disease in Canada [1]. The number of confirmed Canadian cases of human Lyme disease was 2,595 in 2021, an eighteen-fold increase above 2009 when it was designated a nationally notifiable disease [2]. The eastern provinces of Ontario, Québec, and Nova Scotia annually report most

cases in Canada; together they accounted for more than 95% of the confirmed cases in 2021 [1]. *Ixodes scapularis* (the blacklegged tick) is the vector of Lyme disease in these regions, where populations of this obligate parasite are rapidly expanding beyond its previously documented range and continue to establish in new areas [3–5].

The environmental risk of Lyme disease is defined by the density of *I. scapularis* ticks and their prevalence of *B. burgdorferi* infection. In Ontario and Quebec, forests – particularly those dominated by deciduous tree species – provide the ideal environmental conditions for tick survival through all developmental life stages [6]. The blacklegged tick thrives in wooded habitats that provide dense canopy cover, forest floor vegetation, and suitable densities of vertebrate hosts [7–9]. Immature stages of *I. scapularis* feed on rodents, including white-footed mice (*Peromyscus leucopus*), which are important reservoir hosts for *B. burgdorferi* [10], or birds, while adult female ticks feed predominantly on white-tailed deer. Though the list of potential host species may be much longer, evidence in southern Ontario [11] and southwestern Québec [12] points to the relative importance of mice as competent reservoirs in this region. Understory vegetation and leaf litter in the forest microhabitat provide refuge for engorged and questing ticks that protect them from desiccation and extremes of heat and cold [13]. As annual temperatures increase at higher latitudes due to climate change, ticks carried northward by deer and migratory birds can establish new tick populations, resulting in Lyme disease risk emerging in new environments [14]. Past studies established the characteristics of the microhabitats associated with increased environmental risk for Lyme disease [7,15], focusing on the ecological suitability of different woodland types for *I. scapularis* ticks and *B. burgdorferi* transmission.

Yet the impact of forest fragmentation and urban encroachment into woodlands on local Lyme disease risk is not well understood.

Generally, Lyme disease risk has an inverse relationship with urban intensity, where highly developed areas contain little or no tick habitat. At the same time, urban expansion impacts the landscape around cities. Many Canadian metropolitan areas, including Ottawa, Ontario, experienced more rapid growth at the urban fringe and in the surrounding suburbs than through city centre intensification between 2016 and 2021 [16]. These anthropogenic changes can manifest as the fragmentation of regional forests surrounding built-up land [17]. A common result is a mosaic of new developments mixed with numerous small forest patches or degraded forest complexes, which result in larger forest edge density and ecotonal habitat area.

Ecotonal habitat is linked to increased opportunities for interaction between humans and wildlife, including with blacklegged ticks [18], and is associated with higher tick-borne disease risk [19–22]. Early studies exploring a connection between forest edge and tick abundance primarily focused on forest edge shared with herbaceous land cover and rarely with residential land [23–26]. Recent studies of peri-urban green space and urban parks also focus on the type of vegetative habitat present, reporting heterogeneity in the presence and density of ticks in public spaces [27–29]. Yet, in the United States and Canada, evidence from a variety of settings and regional scales supports the association of woodland-residential ecotones with increased risk of Lyme disease [30–33]. In the northeastern United States, it is thought that exposure to ticks is mainly peridomestic though the evidence for this focuses on study areas where both the pathogen and vector have long-established endemicity [34–39]. This regional understanding of Lyme

disease risk in the local landscape does not necessarily translate to residential settings experiencing the emergence of blacklegged tick populations where there may be more heterogeneity in tick population densities and infection prevalence – thus also the environmental risk of Lyme disease – at fine spatial scales.

In their recent metanalysis, Fischhoff et al. (2019) identified that neighbourhood-level factors (e.g., woods adjacent to or within 500 metres of a resident's yard) are more predictive of tick bites and Lyme disease incidence than characteristics of the residential yards themselves [40]. Moon et al. (2019) similarly identified the need to consider peridomestic forest configuration at finer geographic scales (e.g., vicinity of residential yards compared to larger communities; cities compared to boroughs or townships) to better understand landscape risk factors associated with Lyme disease incidence [41]. Meanwhile, Keesing et al. (2023) studied discrete residential properties in New York and found a positive correlation between the proportion of forested property and tick abundance, yet no association with domestic indices of forest fragmentation [42]. Other studies demonstrate that white-footed mice avoid the residential forest edge in favour of woodland interior, suggesting that environmental control measures are best focused within peridomestic woodlands rather than in the habitat along the edge [43,44].

These aspects of Lyme disease ecology are rarely analyzed simultaneously and at a fine scale where tick habitat and human activity intersect. Issues associated with Lyme disease risk in urban and peri-urban settings continue to attract significant research interest, with the focus ranging from property-level factors to urban greenspaces and in settings of emergent and established risk. Maupin et al. [35] studied woods and unmaintained edges on residential properties in an endemic

area of New York state, finding that nymphal and adult ticks were abundant in each of the habitats. In the United Kingdom, Hansford et al. [29] found that the highest densities of infected nymphs were associated with edge habitat between woods and parks or grasslands in their evaluation of tick abundance in recreational urban greenspaces. In a region of New York with more recent emergence of Lyme disease risk, Piedmonte et al. [45] measured tick abundance and pathogen prevalence at sixteen urban and rural sites, concluding that woodland habitat was an important driver of tick density compared to edge. Gregory et al. [46] focused their analysis on residential property-level factors on Staten Island, another area of emergent risk in New York, and determined that this region possesses considerable risk in residential yards that appears driven by a property's surrounding canopy cover. Through comparisons between forests, lawn, and gardens on individual residential properties in a different area of New York, Keesing et al. [42] found forested areas on properties featured greater tick abundance than either lawns or gardens, but there was high variance in the abundance of ticks on lawns between neighbourhoods. Each of these projects measures the entomological hazard at several instances during the active tick season, at either sites distributed across a region or on specific properties of recruited participants. What is emphasized less in this extensive attention to urban risk is a "One Health" approach [47] – paying attention to both the involvement of wildlife in the enzootic transmission cycle of tick-borne pathogens and the integration of peri-urban residential communities with greenspace through trails and pathways that lead to more human activity in areas of risk. Dumas et al. [27] evaluated associations of habitat and host species abundance with tick densities in southwestern Québec, though their intent was to demonstrate the heterogeneity of tick densities across a peri-urban natural park. In the Canadian context, where the recent and

ongoing invasion of blacklegged tick populations means residents are unfamiliar with the local public health threat posed by Lyme disease, urban risk is understudied.

The objective of this study was to characterize the environmental risk for Lyme disease, at a fine local scale and in a region of ongoing blacklegged tick emergence, across an urban development gradient. We defined this gradient in terms of residential, woodland, and residential-woodland interface (i.e., the ecotonal area between the two, hereafter referred to as 'interface' for conciseness) zones. Guided by the *a priori* hypothesis that the local density and infection prevalence of nymphal and adult blacklegged ticks is higher in the woodland and ecotone transition relative to residential areas, we aimed to quantify these associations in peri-urban neighbourhoods. The nymphal life stage is the smallest tick instar that may carry *B. burgdorferi* infection and is challenging to detect on a human host, posing the most significant threat to public health [48]. Moreover, the detection of multiple life stages over consecutive years provides evidence of established tick populations, which pose greater environmental risk [49]. Our findings can help municipal and public health officials inform residents in areas of increased peridomestic risk of necessary Lyme disease prevention and intervention measures.

6.2.5 Results

6.2.5.1 Descriptive statistics

We completed 2,736 quadrat observations from twelve grouped neighbourhood zones (three zones in each of N1-N4) in western Ottawa (Figure 6.1) through nineteen rounds of tick drag sampling in 2020 and 2021. A total of 537 *I. scapularis* ticks were collected, of which 123 were

nymphs, 300 were adults, and 114 were larvae (Table 6.1). More than half (54%) of the total ticks were collected in N2, three-quarters of which were from the woodland zone. The residential zone in N1 was the only area where we found no ticks of any stage over the entire study period. Also, no nymphal ticks were collected from the residential zone of N4. At least one adult tick was collected in the residential zone of all neighbourhoods except N1. Nymphs were present in the interface and woodland zones of all four neighbourhoods, with the total number ranging from 3 (N4) to 10 (N1) in interface zones and from 7 (N4) to 61 (N2) in woodlands. The difference in the number of adult ticks collected from the interface (22) and woodland (28) zones of N1 was small, while adult ticks collected from the other neighbourhoods' interface zones were less than half of their woodland totals. Nymphs were collected most often between May and July, while adults were active between May and June and from September to the end of the study season in both years (see Figure S6.1). We collected larvae in all but one (N4) of the three study neighbourhoods. Though we observed none at residential sites, larval counts in N2 and N3 were higher in the interface (5 larvae collected in each) and woodlands (21 and 22, respectively). The interface zone of N1 proved to be the exception. In this zone, we found more than half (61) of all larvae collected – 50 of these in one sampling effort.

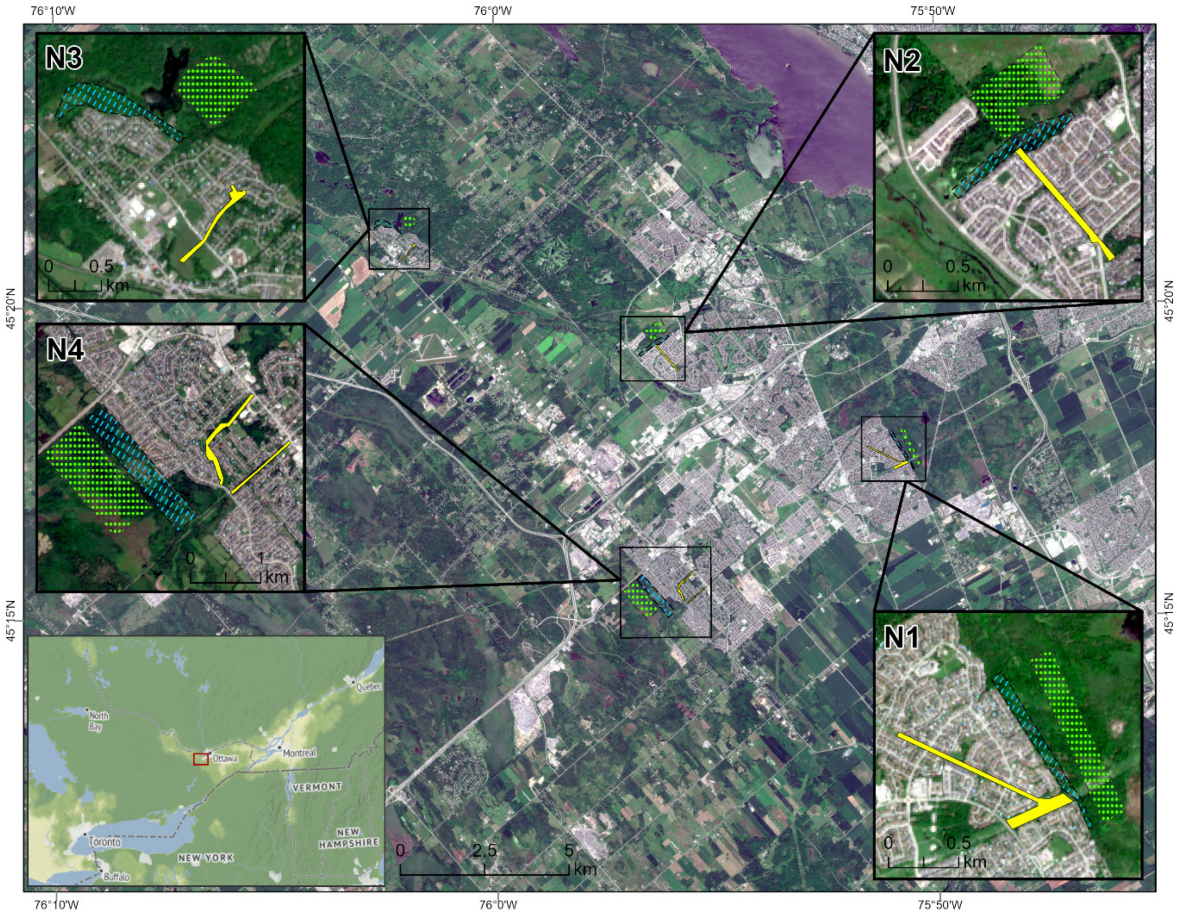


Figure 6.1 Location of residential (solid yellow fill), interface (light blue hatched-line fill), and woodland (bright green dot-hatched fill) sampling zones within each neighbourhood of western Ottawa: N1, N2, N3, and N4. The depicted zonal boundaries are approximations that include the locations of each drag sampling transect used during data collection, drawn to highlight their location and aid in visibility on this map. Basemap

image is Copernicus Sentinel-2 data (2023), accessed and used in accordance with the regulations of the European Union. Context map base layer by Stamen Design, under CC BY 4.0, with data by OpenStreetMap, under the Open Database License (ODbL).

Table 6.1 Total *Ixodes scapularis* ticks collected of each life stage with mean nymphal and all-stage *Borrelia burgdorferi*-infection prevalence and 95% confidence intervals (95% CI) by neighbourhood and zone.

Neighbourhood	Zone	Adults	Nymphs	Larvae	Total	Infected adults	Infected nymphs	Nymphal infection prevalence % (95% CI)	All-stage infection prevalence (95% CI)	*Haemaphysalis spp.* Larvae + Nymphs
N1	Residential	0	0	0	0	0	0	n/a (n/a)	n/a (n/a)	0
	Interface	22	10	61	93	8	0	0 (n/a)	25 (7, 37)	1
	Woodland	28	17	0	45	8	2	12 (0, 38)	22 (10, 37)	0
	N1 Total	50	27	61	138	16	2	7 (0, 21)	23 (13, 33)	1
N2	Residential	1	3	0	4	0	1	33 (0, 100)	25 (0, 100)	0
	Interface	64	6	5	75	21	3	50 (2, 100)	34 (22, 48)	1
	Woodland	129	61	21	211	50	14	23 (15, 37)	34 (22, 39)	0
	N2 Total	194	70	26	290	71	18	26 (17, 46)	34 (25, 39)	1
N3	Residential	1	1	0	2	0	1	100 (n/a)	50 (0, 100)	0
	Interface	7	4	5	16	3	1	25 (0, 100)	36 (1, 63)	0
	Woodland	15	11	22	48	5	1	9 (0, 31)	23 (6, 44)	2
	N3 Total	23	16	27	66	8	3	19 (0, 43)	28 (13, 43)	2
N4	Residential	2	0	0	2	0	0	n/a (n/a)	n/a (n/a)	0
	Interface	8	3	0	11	3	2	67 (0, 100)	45 (10, 81)	0
	Woodland	23	7	0	30	9	2	29 (0, 90)	37 (20, 63)	4
	N4 Total	33	10	0	43	12	4	40 (5, 95)	37 (24, 57)	4
All	Residential	4	4	0	8	0	2	50 (0, 100)	25 (0, 74)	0
	Interface	101	23	71	195	35	6	26 (7, 48)	33 (23, 41)	2
	Woodland	195	96	43	334	72	19	20 (12, 33)	31 (23, 36)	6
Overall		300	123	114	537	107	27	22 (16, 34)	32 (25, 36)	8

Of the 123 nymphs collected, 27 (21.9%) tested positive for *B. burgdorferi*, while 107 (35.7%) of the 300 adults collected were infected (Table 6.1). We collected infected nymphal ticks from all zones except for the residential of N1 and N4, and the interface of N1. The infection prevalence among all tested ticks from interface zones was equal to or greater than that of woodland zones. Across all four neighbourhoods and both sampling years, the nymphal infection prevalence was 22% while the combined adult-nymph infection prevalence was 32% (Table 6.1).

Peromyscus species mice were present in all neighbourhoods and zones. In total, we sampled 812 mice of the target species. *Peromyscus leucopus* (i.e., white-footed mice) comprised 69% of sampled mice across all neighbourhoods, with *P. maniculatus* (i.e., deer mice) representing 27%. *Peromyscus* spp. mice were collected in the greatest abundance in N1 and N4, with 40% and 35% of the total, respectively (Table 6.2). We collected most mice from the residential zone of each neighbourhood, except for N3 where we collected the most from the woodland zone (Table 6.2). The prevalence of *B. burgdorferi* infection among all sampled mice was 11% (Table 6.2), and 96% of infected mice were white-footed mice; only 4 sampled deer mice tested positive (Table S6.1). Neighbourhood prevalence of *B. burgdorferi* infection among all mice ranged from 6% (N4) to 18% (N2). The residential zone of N1 was the only residential area with mice that tested positive for *B. burgdorferi*. Among *P. leucopus* mice, *B. burgdorferi* prevalence was between 17% and 32% in interface zones and 19% and 53% in woodland zones. Overall, 57% of the infected mice we sampled were collected in woodland zones (Table S6.2). The mean deer foraging intensity was 0.5 events (i.e., photos of unique deer) per 100 trap-hours, with a range from 0.2 (N4) to 1.1 (N1). All zones of N1 exhibited the highest deer foraging intensity during

3788 the period our trail cameras were in place. This neighbourhood's residential zone saw more
3789 unique events (1.8 per 100-trap hours) than any other study zone (Table 6.2).

Table 6.2 Total *Peromyscus* species mice collected, zonal abundance (mice per 100 trap-nights), *Borrelia burgdorferi* infection prevalence, and mean deer foraging intensity (events per 100 trap-hours) by neighbourhood and zone ('R': residential; 'I': interface; 'W': woodland)

Neighbourhood	Zone	*P. leucopus*			*P. maniculatus*			*P.* sp.[a]		Mean deer foraging intensity
		Total	Abundance Index	Infection prevalence	Total	Abundance Index	Infection prevalence	Total	Abundance Index	
N1	R	66	5.5	4.5	56	4.7	0.0	6	0.5	1.8
	I	65	5.4	18.5	26	2.2	3.8	3	0.3	0.9
	W	77	6.4	28.6	25	2.1	4.0	2	0.2	0.6
	Total	208	5.8	17.8	107	3.0	1.9	11	0.3	1.1
N2	R	32	2.7	0.0	9	0.8	0.0	0	0.0	0.0
	I	22	1.8	31.8	11	0.9	0.0	1	0.1	0.1
	W	21	1.8	52.4	6	0.5	0.0	0	0.0	0.4
	Total	75	2.1	24.0	26	0.7	0.0	1	0.03	0.2
N3	R	20	1.7	0.0	1	0.1	0.0	1	0.1	0.6
	I	27	2.3	18.5	10	0.8	0.0	0	0.0	0.2
	W	31	2.6	32.3	9	0.8	11.1	1	0.1	0.7
	Total	78	2.2	19.2	20	0.6	5.0	2	0.1	0.5
N4	R	109	9.1	0.0	29	2.4	0.0	12	1.0	0.0
	I	58	4.8	17.2	30	2.5	3.3	3	0.3	0.2
	W	36	3.0	19.4	5	0.4	0.0	2	0.2	0.3
	Total	203	5.6	8.4	64	1.8	1.6	17	0.5	0.2
Overall		564	3.9	15.4	217	1.5	1.8	31	0.2	0.5

[a] No *Peromyscus* sp. mice tested positive for *B. burgdorferi*

We detected significant associations between all ecological characteristics and both sampling neighbourhoods and zones ($p < 0.001$). The most common tree species in all neighbourhoods were maples, though the difference in proportions of sampling quadrats dominated by maples compared to coniferous species was smaller in N3 and N4 (Table 6.3). Quadrats in interface and woodland zones were predominantly occupied by maple trees, while the dominant species among residential quadrats was more varied. Full canopy cover (69%) and understory density (41%) most characterized quadrats in woodland zones, though this was also true of N2 in general (Table 6.3). Shallow litter depth was most common in interface and woodland quadrats. Dry soil humidity characterized the majority of the neighbourhood and zonal quadrats.

Table 6.3 Proportions (%) of sampling quadrats with the recorded observation during June 2020 and 2021 site visits within each neighbourhood and each zone type, with descriptive statistics for continuous measurements.

		Neighbourhoods				Zones		
Characteristic	Value	N1 (n=72)	N2 (n=72)	N3 (n=72)	N4 (n=72)	Residential (n=96)	Interface (n=96)	Woodland (n=96)
Dominant tree species	ash	17	6	7	11	16	10	4
	maple	56	50	39	28	32	55	42
	cedar	0	7	7	14	2	8	10
	coniferous	8	11	33	22	30	8	19
	other decid.	19	26	14	25	20	19	25
Understory density	bare	47	0	24	42	51	23	10
	sparse	22	17	29	44	19	31	34
	dense	9	18	7	8	2	15	15
	full	22	65	40	6	28	31	41
Litter layer depth	none	47	18	37	45	69	31	10
	shallow	40	64	46	51	22	53	76
	moderate	13	18	13	4	9	13	14
	deep	0	0	4	0	0	3	0
Canopy cover mean (s.d.)		48.3 (47.9)	86.1 (26.1)	71.7 (40.7)	22.1 (33.2)	26.5 (37.5)	69.7 (41.0)	75.0 (39.5)
Litter layer depth mean (min-max)		1.11 (0-5)	1.30 (0-5)	1.20 (0-10)	0.87 (0-4)	0.55 (0-5)	1.35 (0-10)	1.46 (0-5)
Soil humidity mean (s.d.)		13.4 (5.7)	28.7 (20.9)	28.9 (23.0)	12.9 (4.8)	24.0 (23.5)	20.9 (14.9)	18.2 (12.6)
P. leucopus abundance (mice per 100 trap-nights) mean (s.d.)		5.8 (1.6)	2.1 (0.7)	2.2 (0.5)	5.6 (2.7)	4.7 (3.2)	3.6 (1.8)	3.4 (1.8)
P. leucopus *B. burgdorferi*-infection prevalence % (95%CI)		16.8 (7.6, 26.0)	28.4 (10.6, 46.2)	17.2 (5.4, 29.0)	12.2 (3.9, 20.5)	0.8 (0.0, 2.2)	21.3 (15.5, 27.1)	33.9 (24.5, 43.3)
Deer intensity (deer per 100 trap-hours) mean (s.d.)		1.1 (0.6)	0.2 (0.3)	0.5 (0.3)	0.2 (0.1)	0.6 (0.8)	0.4 (0.3)	0.5 (0.3)

6.2.5.2 Statistical models

Compared to residential zones, nymphal density was between 4 (interface, 95% confidence interval (95%CI): 1.19-15.03, $p < 0.001$) and 15 (woodland, 95%CI: 4.40-49.85, $p < 0.001$) times greater when controlling for other factors (Table 6.4), presenting a strong gradient effect across zonal habitat types. The association between nymphal infection prevalence and woodland

zones was similarly strong (odds ratio (OR): 13.62, 95%CI: 2.07-89.58, p = 0.007), though the relationship with interface zones was not statistically significant (Table 6.4). Analyses that assessed the density and infection prevalence of all potentially infectious ticks (i.e., nymphs and adults) again demonstrated a strong and significant zonal gradient effect (Table 6.4). The density of nymph and adult ticks was nearly 22 times greater in interface zones and over 31 times greater in woodland zones relative to those in residential zones. Moreover, the infection prevalence of all tested ticks was nearly 15 times greater in interface zones than in the residential (OR: 14.90, 95%CI: 3.15-61.15, $p < 0.001$) and just over 24 times greater in woodlands (OR: 24.23, 95%CI: 6.37-125.14, $p < 0.001$). Though a substantial overlap between the confidence intervals for interface and woodlands zones existed for all metrics, their estimates relative to residential zones were statistically significant ($p < 0.001$).

Table 6.4 Rate ratios (RR) for associations with *I. scapularis* nymphal and nymph and adult density and odds ratios (OR) for associations with *B. burgdorferi* infection prevalence of *I. scapularis* nymphs and ticks. All models are adjusted for sampling month, year, and repeated measurements in neighbourhoods. Estimates are reported with Wald 95% confidence intervals (95% CI) and *P* values.

	Nymphal density		Nymphal infection prevalence		Nymph and adult density		Nymph and adult infection prevalence	
Variable	RR (Wald 95% CI)	*P* value	OR (Wald 95% CI)	*P* value	RR (Wald 95% CI)	*P* value	OR (Wald 95% CI)	*P* value
Dominant tree species (ref: ash)								
maple	1.45 (0.29, 7.21)	0.654	0.46 (0.04, 4.79)	0.515	1.55 (0.79, 3.02)	0.199	1.11 (0.38, 2.91)	0.842
cedar	2.52 (0.42, 15.27)	0.314	0.31 (0.02, 5.50)	0.425	1.29 (0.58, 2.88)	0.531	1.04 (0.26, 2.89)	0.948
other coniferous	0.98 (0.15, 6.43)	0.983	0.00 (n/a)	0.973	1.57 (0.70, 3.54)	0.276	0.22 (0.03, 0.96)	0.069
other deciduous	0.91 (0.17, 4.82)	0.910	0.08 (0.01, 1.27)	0.073	1.09 (0.54, 2.20)	0.801	0.75 (0.27, 2.25)	0.602
Canopy cover (+10%)	1.04 (0.92, 1.18)	0.523	1.08 (0.87, 1.34)	0.494	0.99 (0.93, 1.06)	0.737	0.96 (0.88, 1.07)	0.452
Understory density (ref: bare)								
sparse	0.63 (0.19, 2.06)	0.447	0.03 (0.00, 0.24)	0.001	1.36 (0.73, 2.51)	0.332	0.79 (0.33, 2.45)	0.635
dense	0.15 (0.03, 0.76)	0.022	0.02 (0.00, 0.42)	0.011	1.32 (0.63, 2.74)	0.464	0.79 (0.30, 2.75)	0.676
full	0.91 (0.26, 3.15)	0.876	0.13 (0.02, 0.91)	0.040	2.49 (1.30, 4.78)	0.006	1.17 (0.47, 3.94)	0.772
Litter layer depth (ref: none)								
shallow	3.80 (1.22, 11.80)	0.021	15.49 (1.70, 141.12)	0.015	1.65 (1.00, 2.70)	0.049	2.54 (0.95, 4.80)	0.026
moderate	2.90 (0.85, 9.93)	0.090	6.56 (0.60, 71.98)	0.124	0.92 (0.49, 1.70)	0.786	1.55 (0.39, 3.08)	0.392
Soil moisture (+10%)	1.21 (1.01, 1.45)	0.036	1.48 (1.13, 1.93)	0.004	1.02 (0.91, 1.14)	0.761	1.15 (0.95, 1.30)	0.060
P. leucopus abundance index			0.85 (0.62, 1.17)	0.329			0.84 (0.63, 1.04)	0.165
Mean deer foraging intensity (x 100)	2.21 (0.97, 5.03)	0.060	0.72 (0.13, 4.04)	0.711	1.53 (0.94, 2.49)	0.087	1.67 (0.58, 2.77)	0.192
Zone type (ref: residential)								
interface	4.24 (1.19, 15.03)	< 0.001	1.69 (0.25, 11.45)	0.593	21.79 (9.94, 47.77)	< 0.001	14.90 (3.15, 61.15)	< 0.001
woodland	14.81 (4.40, 49.85)	< 0.001	13.62 (2.07, 89.58)	0.007	31.33 (14.25, 68.86)	< 0.001	24.23 (6.37, 125.14)	< 0.001

In both models of nymphal tick outcomes, we identified associations with several aspects of the forest microhabitats. Shallow litter depth (i.e., less than 2 centimetres) compared to no leaf litter was associated with nearly 4 times greater density of nymphs (95%CI: 1.22-11.80) and a more than 15-fold higher nymphal infection prevalence (95%CI: 1.70-141.12). A ten-percent higher soil moisture above average was also associated with a 20% higher nymphal density (rate ratio (RR): 1.21, 95%CI: 1.01-1.45) and a nearly 50% greater infection prevalence among nymphs (OR: 1.48, 95%CI: 1.13-1.93). We noted a strongly negative relationship between nymph outcomes and understory density, particularly with dense understory relative to bare (nymphal density RR: 0.15, 95%CI: 0.03-0.76; infection prevalence OR: 0.02, 95%CI: 0.00-0.42). However, a full understory was associated with a 2.5 times greater density of nymphs and adults together compared to a bare understory (RR: 2.49, 95%CI: 1.30-4.78).

Tick densities predicted by the average marginal effects demonstrate zonal and neighbourhood associations with the environmental risk of Lyme disease when site-specific and ecological characteristics are held at their mean or referent value (Figure 6.2; Table S6.3). Heterogeneous tick densities exist between the studied neighbourhoods; zones in N1 and N2 exhibited greater densities compared to those in N3 and N4 (Figure 2A and 2C). Overall, predicted nymphal density was 0.05 per 100 m^2 in interface zones compared to 0.17 per 100 m^2 in woodlands. This zonal gradient on nymphal density was most evident in N2 (0.07 per 100 m^2 and 0.24 per 100 m^2 in the interface and woodland zones, respectively). The same gradient effect across zonal habitat types was present in predictions of the density of all potentially infectious ticks (i.e., nymphs and adults), both within and independent of neighbourhoods. Diagnostic plots of residuals indicated

3882 good model fits given the chosen response distributions, covariates adequately explaining the
3883 outcomes, and the absence of influential outliers (Figures S6.2-S6.5).

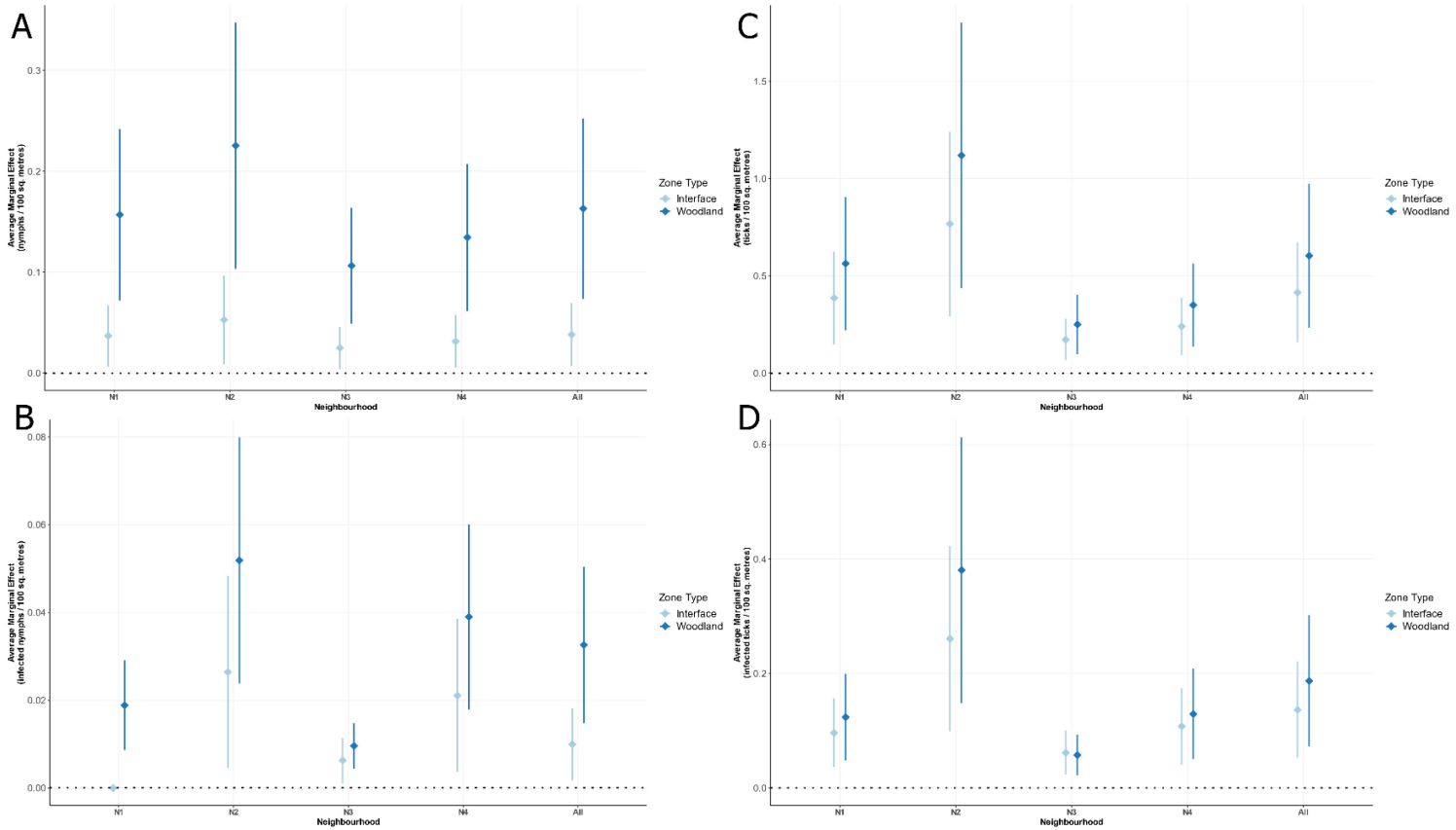


Figure 6.2 Average marginal effect on nymphal density (A), density of infected nymphs (B), tick (nymph and adult) density (C), and density of infected adults and nymphs (D) for interface and woodland zones compared to residential, with all other covariates at their mean value. Plots include the zonal effect within each neighbourhood (N1-N4) as well as independent of neighbourhood. The density of infected nymphs (B) and infected adults and nymphs combined (D) is determined by the product of the predicted density and the observed infection prevalence reported in Table 6.1.

6.2.6 Discussion

Our study provides a fine-scale examination of Lyme disease environmental risk along a landscape gradient, demonstrating elevated risk in interface and woodland zones relative to residential paths and trails. The density and infection prevalence of nymphal ticks in these ecotonal zones were higher than those found in residential zones, highlighting the significant role they hold in the Lyme disease risk present in neighbourhoods featuring residential areas with integrated greenspace. Studies of habitat types within urban woodland parks of England found the highest densities of *I. ricinus* nymphal ticks in woodland edge sites, with evidence of established populations in grassland, woodland, and woodland edge habitats of urban and peri-urban greenspaces [28,29]. Conversely, in New York state, Horobik et al. found that densities of *I. scapularis* ticks and infected ticks were both higher in forests than at forest-field edge, concluding that edges do not pose a higher risk than the forests themselves [50]. However, each of these studies examined the entomological risk present at the edge of forests with open grassland. We examined the forest edge that specifically interfaces with the boundary of residential properties. One hypothesized mechanism underlying the effect that human-driven landscape change has on Lyme disease risk is termed “ecological release”, wherein populations of a species increase due to changes that remove constraints limiting their expansion. A relevant example of this is the creation of new forest edges or clearings – specifically when these border human residential areas that provide new resources and nesting opportunities favoured by, for example, white-footed mice [22]. By accounting for possible differences in the abundance of white-footed mice, which is believed to be the primary reservoir in this region [11,12], in the sampled zones, as well as characteristics of the microhabitat known to impact blacklegged tick survival, we shed light on the role of interface zones on Lyme disease risk.

Direct comparison of total tick density between the unique zones and neighbourhoods indicates heterogeneity at this scale. Densities of nymphs and all potentially infectious ticks in N2 reflected previous estimates for the Ottawa municipal region [51]. The densities identified in each of the three remaining study neighbourhoods were lower. Still, despite a small sample size of infected nymphal ticks from these three neighbourhoods, we detected an infection prevalence that also supports estimates reported previously for this region, indicating the presence of Lyme disease environmental risk [51]. It is notable, however, that the prevalence of infection among the collected nymphs was consistently higher in interface zones compared to woodlands, apart from N1 where no infected nymphs were sampled. We also note that, while evaluating the density of nymph and adult ticks together is common, doing so carries potential issues in the assessment of infection rates given that prevalence in adult ticks is typically greater, having potentially fed twice on reservoir hosts. Still, the zonal differences we detected underscore the importance of considering the ecological relationship with reservoir hosts along the environmental gradient we examined.

Our results from sampled *Peromyscus*-species mice indicated higher abundance in residential zones while *B. burgdorferi* prevalence was highest in woodland habitats. This supports previous evidence demonstrating greater white-footed mouse abundance at sites with less forested area within a 500-metre radius yet lower *B. burgdorferi* prevalence than their within-woodland kin [44]. Together, these results are demonstrative of the differences in scale-based associations of landscape edge effects. Though the difference in nymphal infection prevalence we measured for the interface zone was not statistically significant, the findings of Piedmonte et al. corroborate a

similarity in prevalence among all potentially infectious ticks through their exploration of multi-scale habitat effects on tick-borne pathogen prevalence [45]. Continued surveillance in residential-woodland ecotonal habitats, where the potential for human-tick encounters is high, will improve our understanding of this relationship. And, while the *B. burgdorferi* prevalence of white-footed mice observed in our data appears to support its role in enzootic transmission within this region, the involvement of other potential host species remains understudied. Additional rigorous evaluation of host community composition would help to more fully characterize the transmission dynamics between these zonal settings [52,53].

Several limitations of this study should be considered along with the results described above. Weak relationships between some ecological observations and the evaluated outcomes may be due to the generalization of each 50 m^2 sampling area to discrete observations. We cannot dismiss the possibility that environmental measurements were subject to observer bias that resulted in misclassification. While it is a strength of this study design to investigate microhabitat characteristics of the sampling area where ticks were collected, the precision of effects for ecological characteristics could be further improved by quantifying the same measures. For example, obtaining imagery from drones flown along sampling transects and using machine learning image processing methods to inventory and calculate distributions of tree species would be a more efficient and less costly approach to quantify these areas of risk and guide field sampling. In terms of zonal factors, the final models we evaluated were adjusted for the involvement of white-footed mice and deer in the outcome measures, but we did not account for the structure or diversity of the broader vertebrate host community; we were not able to focus on other small or medium-sized mammal species. While we adjusted for study neighbourhood in our

models, differences in landscape configuration of zones within neighbourhoods that were not measured may impact the results and should be an area for further research. We also determined tick density and infection prevalence using drag sampling which is less resource-intensive than collection of ticks from small mammal hosts but may be less efficient [54–56], though its effectiveness as a method to identify *I. scapularis* populations in this region has been shown [57]. We followed rigorous standardized protocols for drag sampling, but stage-differential or non-detection of ticks (false negatives) are a recognized limitation of this method. *I. scapularis* adults are generally easier to collect by drag sampling as some types of terrain more easily dislodge nymphal ticks (N.H. Ogden, personal communication, February 2, 2024). Finally, the prevalence calculations for some of the neighbourhood zones were based on small totals of collected nymphs and adults, which can result in wider confidence intervals due to uncertainty in the estimates [58]. Future research should continue active surveillance in these and additional neighbourhoods and other Canadian regions with emerging tick populations, to further validate these estimates and their relationships.

Urban expansion involves the encroachment of residential developments into natural areas. As suburbs and peri-urban regions continue to change through this practice, it is crucial to understand how new ecotones contribute to local Lyme disease risk. Several past studies connect the quantity of wooded space in and around the residential yard to the increased risk of encounters with host-seeking ticks [35,46]. Yet these findings focus on Lyme disease risk where established residential properties border wooded areas and do not assess where new landscape change integrates existing forest with new residences, trails and pathways. Ours is among the first to quantify the effect of land cover types in different stages of urban development on local

tickborne disease risk, specifically using a "One Health" approach [47] across the residential-to-woodland ecotonal gradient. In this study, we focused on the fine-scale localization of Lyme disease risk within neighbourhoods of a region experiencing the rapid emergence of blacklegged tick populations. By simultaneously modelling the local impact of wildlife host availability, microhabitat characteristics, and stage of land development on the density and infection status of *I. scapularis* ticks, we demonstrated that the environmental hazard of tick-borne diseases is significant at the intersection of urban greenspace and residential properties. These results may help to inform urban planning guidelines regarding the selection and development of sites through the characterization of environmental Lyme disease risk prior to the development of new residential neighbourhoods. Continued surveillance, informing targeted control measures [59], is necessary to ensure that local Lyme disease risk is minimized as new ecotonal "interface" areas allow human tick encounter opportunities. Finally, these effects should be investigated in other settings experiencing blacklegged tick emergence, to better understand the environmental characteristics of Lyme disease hazard and incorporate intervention and control measures into expansion plans.

6.2.7 Methods

6.2.7.1 Study location

Four neighbourhoods across the rural and suburban areas of western Ottawa (Figure 6.1) were selected to assess tick populations, characterize the environmental factors and estimate the abundance of species involved in the *B. burgdorferi* transmission cycle (i.e., *Peromyscus*-species mice and white-tailed deer). Guided by the results of recent active tick surveillance that

4005 established the presence of black-legged tick populations [51], we engaged in partnership and
4006 consultation with the National Capital Commission, Ottawa Public Health, and the City of
4007 Ottawa's Planning Division to arrive at an informed selection of these sites. To identify
4008 characteristics related to varying degrees of proximity to urban and residential development, we
4009 subdivided each neighbourhood into three sampling zones: residential, woodland, and interface
4010 (Figure 6.1). Residential zones consisted of pathways and trails within neighbourhoods between
4011 the back yards of residential properties, while woodland zones were defined as forested areas
4012 adjacent to the developed areas of neighbourhoods and connected to residential areas by trail
4013 networks. Interface zones consisted of trails and wooded edges immediately bordering residential
4014 properties, such that homes or fences remained visible from just inside the tree line.
4015

4016 *6.2.7.2 Tick drag sampling*

4017 Our study area included 36 sites evenly divided across the four neighbourhoods (N1 – N4), with
4018 three sampling zones in each neighbourhood (i.e., residential, woodland, and interface), and three
4019 sites in each sampling zone.
4020

4021 Field collectors experienced in collecting ticks by drag sampling visited each site monthly from
4022 May through October 2020 and biweekly across the same period in 2021. At each site, team
4023 members followed a standard tick-dragging sampling protocol, wherein a one-metre white
4024 flannel sheet is dragged along the ground to collect questing ticks [60]. The starting location for
4025 each tick drag transect was selected based on observations from preliminary site visits that a
4026 continuous linear drag remained in the same zone type without interruption and allowed for

measurement from three consecutive sites across both sampling years. Field collectors stopped every 25 metres to check and remove ticks from the flannel and record the geographical coordinates of the sampling location using a Garmin eTrex 20 GPS, covering 200 metres. In total, the area dragged per sampling visit was 600 square metres in each zone and 1,800 square metres in each neighbourhood. All collected ticks were returned to the lab in specimen tubes, where species and stage were identified by microscope according to standard taxonomic keys [61–63].

6.2.7.3 Ecological characteristics

To ascertain any distinguishing characteristics that might influence the suitability of distinct locations for tick survival, we examined the fine-scale aspects of the microhabitat at each surveillance site. Field collectors recorded site-specific ecological measurements (Table 6.5) derived from several studies of blacklegged tick abundance at every second sampling location (50 metres) in June of both study years. Mid-season values for all variables were used to capture and adjust for general ecological differences across all sites in our analyses.

We identified all categorical variables according to previously established classification keys [9,64–66]. Field researchers also measured the percentage of canopy cover overhead at sampling locations using a spherical densiometer, according to established field protocols [67]. The same study personnel measured litter layer depth with a small ruler perpendicular to the ground, rounding to the nearest centimetre, and measured soil moisture in percentage by inserting a moisture meter probe approximately 4 to 6 centimetres into the soil. In analyses, we also treated

litter depth as a categorical variable with the thresholds used by Talbot et al. [9]: none, shallow (< 2 cm), or moderate to deep (3 to 10 cm).

Table 6.5 Ecological observations and measurements recorded at sampling locations, with description and rationale for consideration.

Variable	Units / Categories	Rationale
Dominant tree species	ash (reference) maple cedar other coniferous other deciduous	Deciduous trees provide heavier leaf litter and have been associated with higher levels of risk. Coniferous trees have been shown to discourage tick establishment due to the absence of leaf litter in some regions [9,68].
Canopy cover	%	A dense or closed canopy cover can protect from weather extremes (cold, wet) and provide more leaf litter [11,15].
Understory density	bare (none present; reference) sparse (visible but no significant coverage) dense (thick, difficult to traverse) full (healthy, covering most of the forest floor)	Habitats with a dense understory may provide better refuges for ticks from extreme weather and a grassy substrate on which to quest [9,66,69–71].
Litter layer depth	none (0 cm; reference) shallow (<2 cm) moderate to deep (3 to 10 cm)	Leaf litter provides a refuge from cold in winter and keeps the microhabitat humid, which contributes to tick survival by protecting them from desiccation [9,11,15,66,71].
Soil moisture	%	In microhabitats, soil moisture is directly related to the relative humidity, which contributes to the ability of ticks to survive [9,66,68,71].

6.2.7.4 Small mammal sampling

Our trapping effort was based on a target sample size of up to 50 individuals per species (i.e., *Peromyscus leucopus,* or white-footed mice, and *Peromyscus maniculatus*, or deer mice) per zone each year, assuming 1 mouse for approximately every 10 trap-nights with additional trap-nights to account for trap failures. Trapping sessions took place in two rounds of two consecutive nights in each neighbourhood zone during the peak period of mouse activity (June to August).

Ethical approval for small-mammal research was obtained from the University of Ottawa Animal Care Committee (permit ME-3079). All animal trapping and handling methods were performed in accordance with the Canadian Council on Animal Care's guidelines involving wildlife [72].

During the two-night sampling period in each neighbourhood zone, field collectors laid 150 Sherman traps, baited with an apple cube, a pinch of oats, and a cotton round, on both sides of the trail. Team members ensured trap placement in two parallel lines ten metres apart, with 5 to 10 metres of distance between each trap in the same line. The exact distance between traps varied depending on the habitat and availability of forested space in each location. Traps were set each evening and checked the following morning. Therefore, our sampling effort was 600 trap-nights per neighbourhood zone in each sampling year, totalling 7,200 trap-nights across all neighbourhoods.

Small mammals captured during the night were briefly removed from traps into a cotton bag to safely measure their weight before removing them for inspection. For all trapped animals of the target species, sex, reproductive condition, length and weight were recorded, attached ticks were collected, and one ear punch biopsy was taken from each ear [73] before the animal was released. Individuals for which the species could not be identified based on field guides were referred to as "*P.* sp." in field records [74]. For any non-target animals trapped (e.g., chipmunks, voles), we identified the species, collected any attached ticks and released them. We did not sample these diurnal species as the capture methods we employed are tailored to nocturnal animals.

6.2.7.5 Pathogen testing

We tested all biopsy ear punches, adult, and nymphal ticks for Borrelia burgdorferi s.s. using quantitative polymerase chain reaction (qPCR) assays according to previously published protocols [75,76]. In short, we extracted total genomic DNA using the QIAamp mini kit (QIAGEN, Mississauga, ON, Canada). With this, we identified Borrelia species using a duplex qPCR assay targeting the 23S ribosomal RNA. We further confirmed the presence of Borrelia burgdorferi s.s. by targeting the ospA gene. We performed amplifications with the BioRad CFX96 Real-Time PCR Detection System and sample analysis with CFX Maestro Software version 2.3 (Bio-Rad Laboratories, Hercules, CA, USA).

6.2.7.6 Deer density

As a proxy of white-tailed deer density in our models of tick outcomes, we calculated deer foraging intensity in each zone as captured by trail cameras. We installed one trail camera at each neighbourhood zone (12 total locations) at the end of June each year to collect images of large mammals active in the area. Every two weeks until the middle of October, field collectors relocated each camera 200 metres along the tick drag sampling site, resulting in 8 camera trap sites per neighbourhood zone. We filtered all collected photographs to select only images of white-tailed deer and totalled the number of use events such that a unique deer captured by the camera counted as one event. To avoid overestimation due to double-counting, photographs with deer captured within a 10-minute interval of the previous capture were considered a single event to allow for the individual's activity to cross in and out of the camera's detection zone. We estimated the foraging intensity at each camera location by dividing the number of events by the total number of camera-hours at the site, as per previously documented calculation methods [77].

We then averaged this number across all twelve installation locations for the camera to arrive at a "foraging intensity" estimate for deer activity in each neighbourhood zone.

6.2.7.7 Statistical analysis

We linked ecological data to the total number of *I. scapularis* ticks of each stage from the current and preceding sampling locations. This resulted in 50-metre-long rectangular quadrats as the unit of analysis, with four quadrats in each of the three sampling sites of all neighbourhood zones (144 in total). Each quadrat was dragged for questing ticks 19 times across the entire study period. Prior to analysis, the most dominant tree species was reclassified as one of 'ash,' 'maple,' 'cedar,' 'other coniferous,' or 'other deciduous' due to low numbers of observations for some deciduous and coniferous tree species as predominant among the sampling quadrats and to focus on effects of species with potential associations identified by Talbot et al. [9]. In all analyses, we mean-centred continuous variables: the proportion of canopy cover, soil moisture, and mean deer foraging intensity.

We performed all statistical analyses using the 'lme4' package in R version 4.1.3. Given the repeated transect measures performed within study neighbourhoods, we built generalized linear mixed models (GLMMs) with a random intercept for neighbourhoods to account for between-neighbourhood differences in the density and infection prevalence of ticks, as well as unmeasured differences in the configuration of neighbourhoods affecting relative distance between zones within neighbourhoods. In each model, we also forced month as an ordinal variable (5 to 10, May to October) to account for seasonal variation in peak activity of different

tick life stages, and we used year as a factor with two levels (2020 and 2021) as an adjustment for interannual variation in tick abundance. To determine the most appropriate statistical distribution for our count data, we used the 'glmer' function to evaluate the association of our main predictor of interest, zone type, with tick densities in Poisson GLMMs. We checked these models for excess observations of zero ticks with the 'check_overdispersion' function from the 'performance' package. As overdispersion was detected, we proceeded with a negative binomial (NB) GLMM via the 'glmer.nb' function and checked the dispersion statistic again. Since the NB distribution adjusted for the overdispersion sufficiently, we deemed a zero-inflated process unnecessary. For models assessing associations with the presence of infected nymphs and adults, we used a Binomial GLMM with the 'glmer' function to estimate *B. burgdorferi* prevalence across our study sites.

For each outcome measure, we tested multivariable conceptual models conceived *a priori*. Negative binomial GLMMs exploring associations with the densities of nymphal and adult ticks included categorical variables (see Table 6.5 for ecological category definitions) for the dominant tree species, depth of leaf litter, understory density, and zone type, as well as continuous measurements for soil moisture, mean deer foraging intensity, and canopy cover. In Binomial GLMMs exploring the *B. burgdorferi* infection prevalence of nymphs and adults, we also included continuous predictors for the abundance and the *B. burgdorferi* infection prevalence of *P. leucopus* mice. We initially considered including predictors for *P. maniculatus* mice but omitted them due to their lower relative abundance between neighbourhoods and the near-total absence of *B. burgdorferi* infection among the sampled deer mice. A check of variance inflation factors among our model terms with the 'performance' package revealed collinearity between *P.*

leucopus infection prevalence and zone type in both Binomial GLMMs. Thus, *B. burgdorferi* infection prevalence in white-footed mice was removed from the final models. For both count models, we calculated predicted tick densities based on the average marginal effects for neighbourhoods and zones with all covariates held at their mean values using the 'margins' package. We also performed residuals diagnostics with the 'DHARMa' package for hierarchical models.

6.2.8 Acknowledgements

The authors would like to thank the City of Ottawa and the National Capital Commission for their consultation and for providing land access permits, which allowed sampling activities in the selected neighbourhoods. We also extend our gratitude to the dedicated field teams at the University of Ottawa for their contributions.

6.2.9 Supporting Information

Table S6.1 *Borrelia burgdorferi* infection status of mice by species

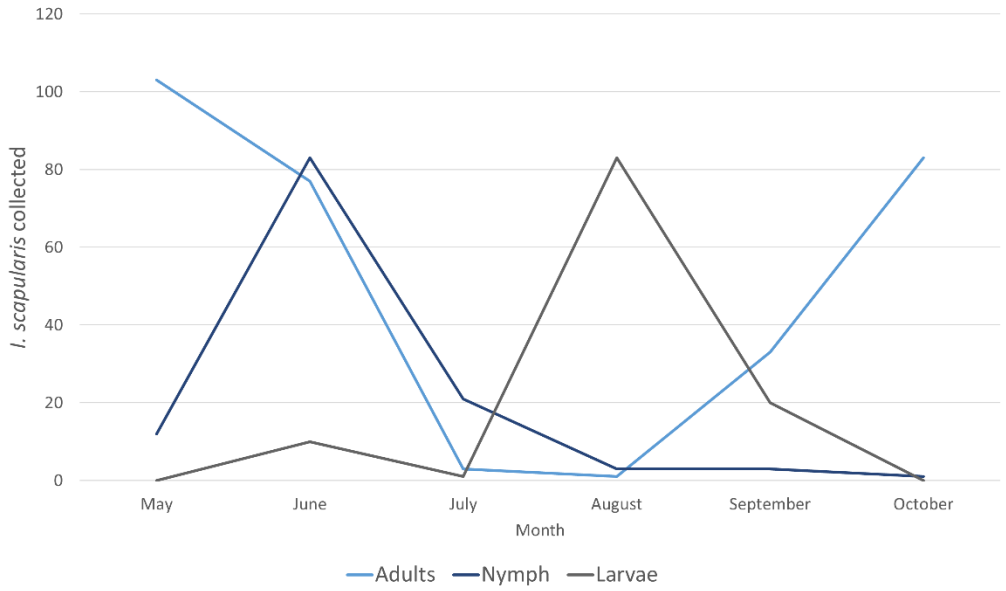
	Infected n (%)	Uninfected n (%)	Total
P. leucopus	87 (96)	477 (66)	564
P. maniculatus	4 (4)	213 (30)	217
Other *P. sp.*	0 (0)	31 (4)	31
Total	91	721	812

Table S6.2 *Borrelia burgdorferi*-infection status of mice by zone and neighbourhood

	Residential		Interface		Woodland		Neighbourhood Total (%)
	Positive	Negative	Positive	Negative	Positive	Negative	
Neighbourhood 1	3	125	13	81	23	81	39 (11.9)
Neighbourhood 2	0	41	7	27	11	16	18 (17.6)
Neighbourhood 3	0	22	5	32	11	30	16 (16.0)
Neighbourhood 4	0	150	11	80	7	36	18 (6.3)
Zonal Total (%)	3 (0.9)		36 (14.0)		52 (24.2)		
Overall proportion of *Bb*-positive mice	3.3		39.6		57.1		

Table S6.3 Predicted nymphal and tick density by neighbourhoods and zones, based on average marginal effects calculated from models, with all other covariates at their mean value. Density of infected nymphs and infected adults and nymphs combined is determined by the product of the predicted density and the observed infection prevalence (Table 6.1).

		Nymphal density (nymphs / 100 m^2)	Tick density (ticks / 100 m^2)	Infected nymph density (infected nymphs / 100 m^2)	Infected tick density (infected ticks / 100 m^2)
N1	Residential	0.01	0.02	0.00	0.00
	Interface	0.05	0.40	0.00	0.10
	Woodland	0.17	0.58	0.02	0.13
	All N1	0.09	0.37	0.01	0.09
N2	Residential	0.02	0.04	0.01	0.01
	Interface	0.07	0.80	0.04	0.27
	Woodland	0.24	1.16	0.06	0.39
	All N2	0.12	0.74	0.03	0.25
N3	Residential	0.01	0.01	0.01	0.01
	Interface	0.03	0.18	0.01	0.06
	Woodland	0.11	0.26	0.01	0.06
	All N3	0.06	0.16	0.01	0.04
N4	Residential	0.01	0.01	0.00	0.00
	Interface	0.04	0.25	0.03	0.11
	Woodland	0.14	0.36	0.04	0.13
	All N4	0.07	0.23	0.03	0.09
All	Residential	0.01	0.02	0.01	0.01
	Interface	0.05	0.43	0.01	0.14
	Woodland	0.17	0.62	0.03	0.19



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4197 **Figure S6.1** Number of ticks of each life stage by month collected, 2020-2021, across all neighbourhoods

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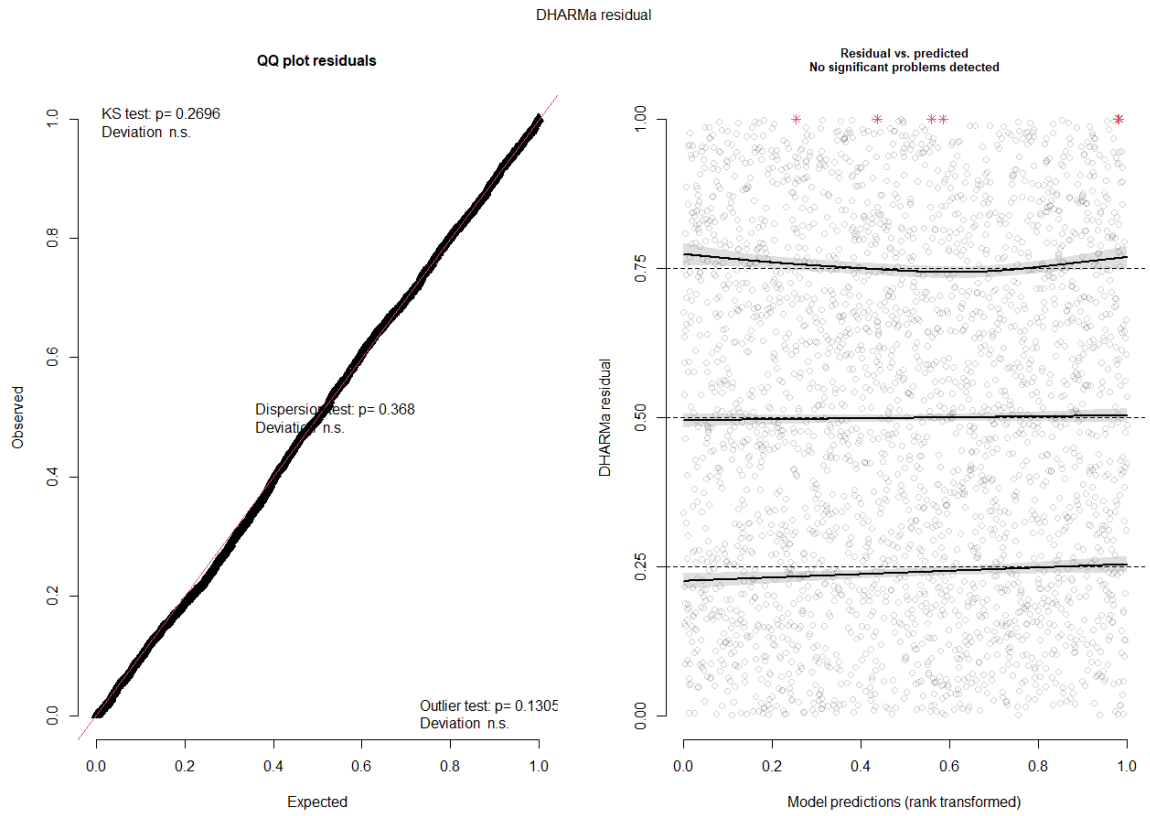
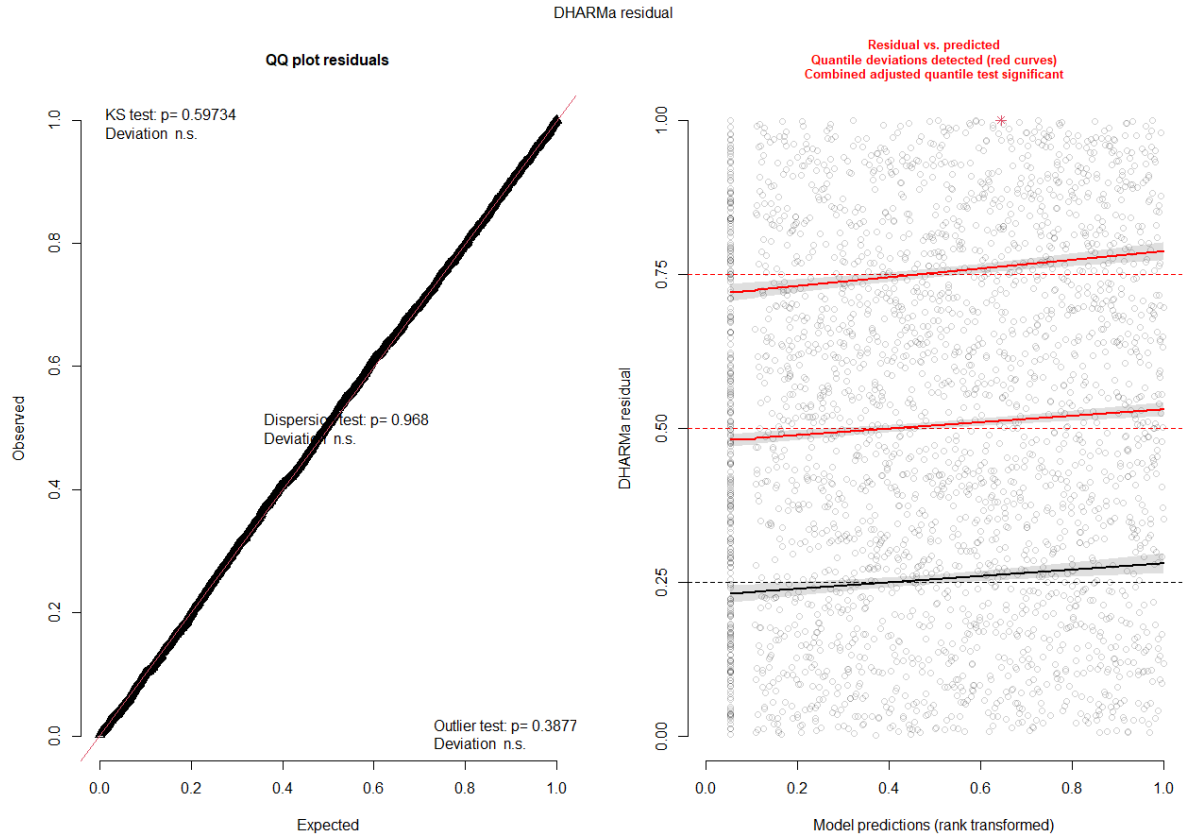


Figure S6.2 Diagnostic residual plots demonstrating negative binomial GLMM fit for the density of nymphal *Ixodes scapularis* ticks.



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4204 **Figure S6.3** Diagnostic residual plots demonstrating Binomial GLMM fit for the *Borrelia burgdorferi*
4205 infection prevalence among nymphal *Ixodes scapularis* ticks.

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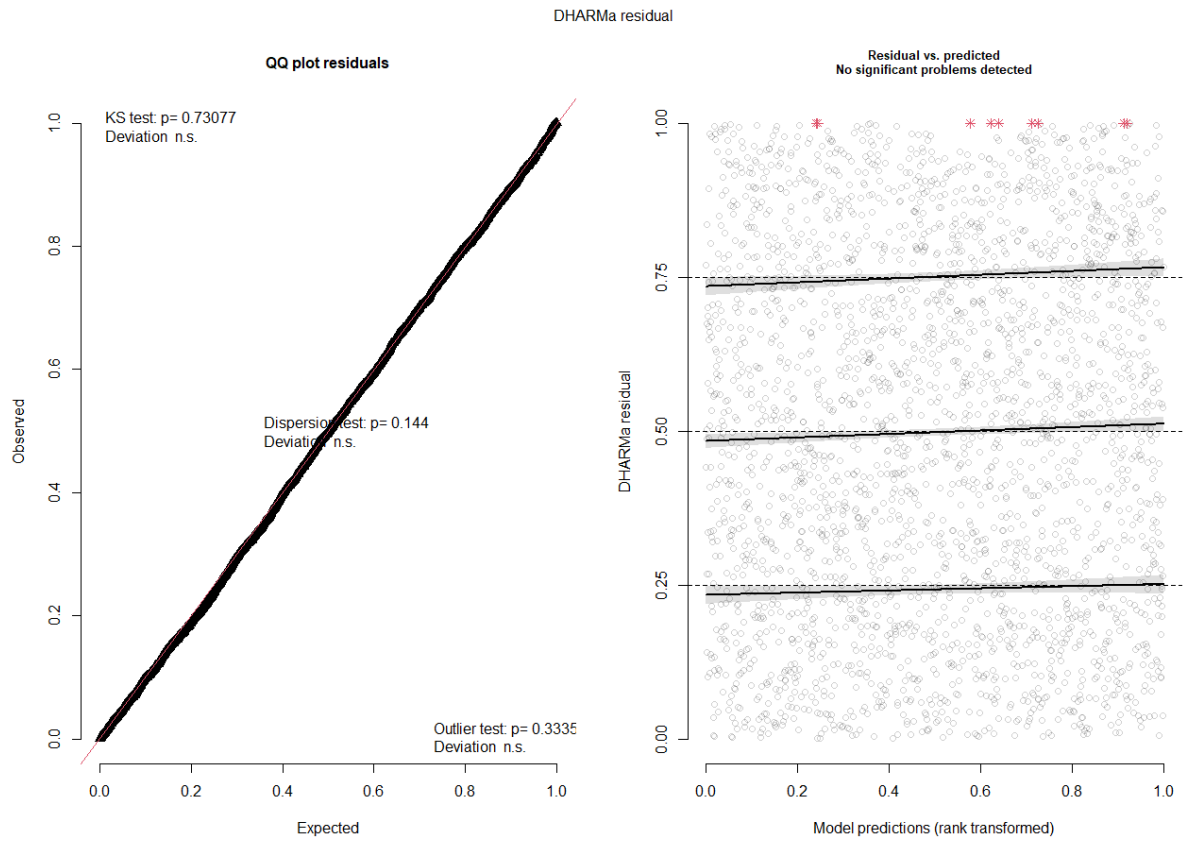

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4208 **Figure S6.4** Diagnostic residual plots demonstrating negative binomial GLMM fit for the density of
4209 nymphal and adult *Ixodes scapularis* ticks.

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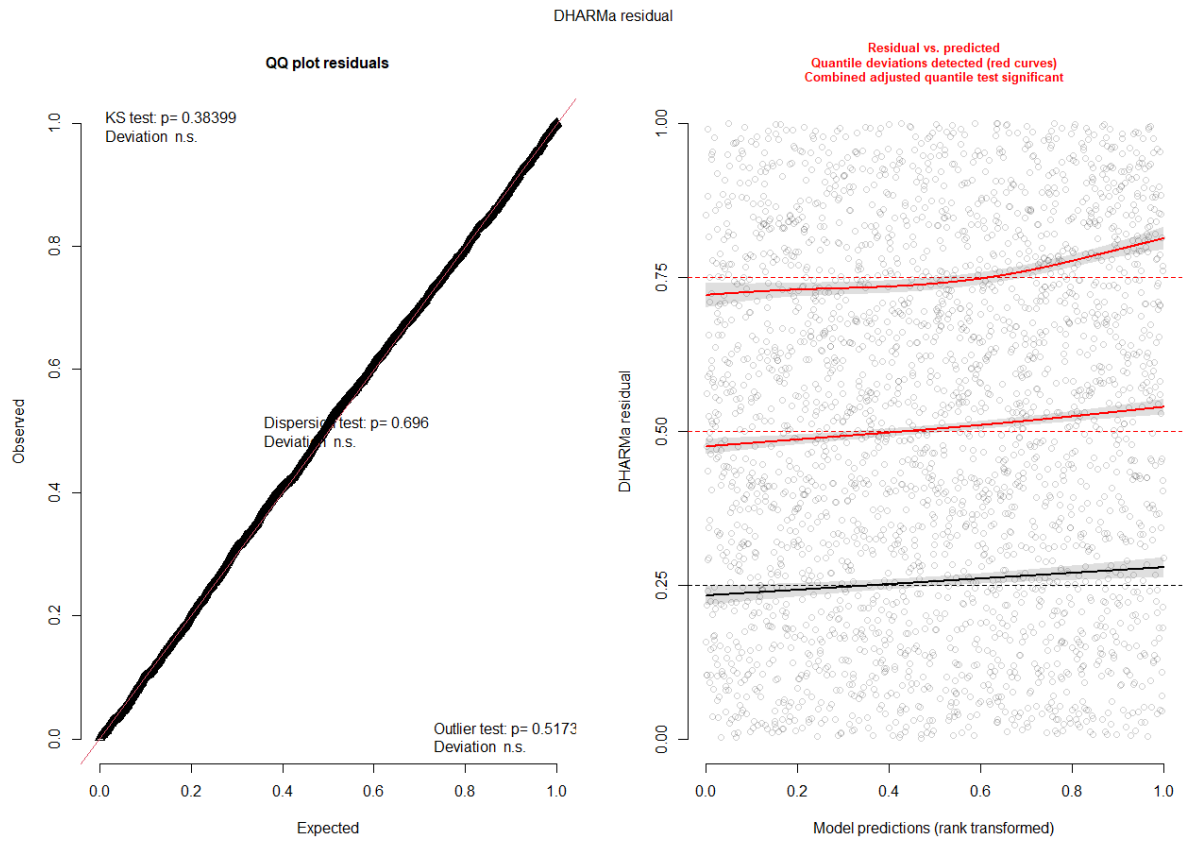

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4212 **Figure S6.5** Diagnostic residual plots demonstrating Binomial GLMM fit for the *Borrelia burgdorferi*
4213 infection prevalence among nymphal and adult *Ixodes scapularis* ticks.

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Chapter 7

Integrated Discussion

The Government of Canada's "Lyme Disease in Canada – A Federal Framework" established that "monitoring the distribution and expansion of the Lyme disease risk areas in Canada" is a public health priority [1]. In the time since this legislation received Royal Assent, climatological models continue to predict the northward range expansion of *Ixodes scapularis* ticks further into Canada [2–4]. Relatedly, Public Health Agency of Canada surveillance reports establish that the proportion of locally acquired Lyme disease cases has risen drastically over the past decade [5–7]; however, this definition of local acquisition conflates residence with travel to established areas of Lyme disease endemicity [8]. Reporting of peridomestic exposures remains uncommon among Canadian Lyme disease cases, yet it does occur [9]. With the expected expansion of Lyme disease risk areas in Canada, it is vitally important to improve our understanding of the factors associated with environmental hazard and personal vulnerability that intersect as fine-scale, local risks to enhance peridomestic prevention and control efforts.

The overall goal of this thesis was to examine how elements of hazard and vulnerability contribute to local Lyme disease risk in Ottawa, Ontario, where previous research substantiates the recent and ongoing emergence of blacklegged ticks [10]. A thematic tenet that runs through my work is the assumption that residential risk is high in regions where the Lyme disease pathogen and vector have long been endemic [11]. Adopting a One Health approach, with Ottawa, Ontario as the focus, I explored this through three lenses (Figure 7.1). First, I analyzed the impact of landscape configuration on local Lyme disease risk at

an ecological, neighbourhood level. Secondly, I explored vulnerability through the results from a survey of knowledge, attitudes, and practices regarding Lyme disease to identify characteristics of individuals with good Lyme disease knowledge as well as strong adoption of protective behaviours. Last, I evaluated surveillance data collected to identify the level of environmental hazard for Lyme disease associated with habitat gradients extending from residential property limits into woodlands.

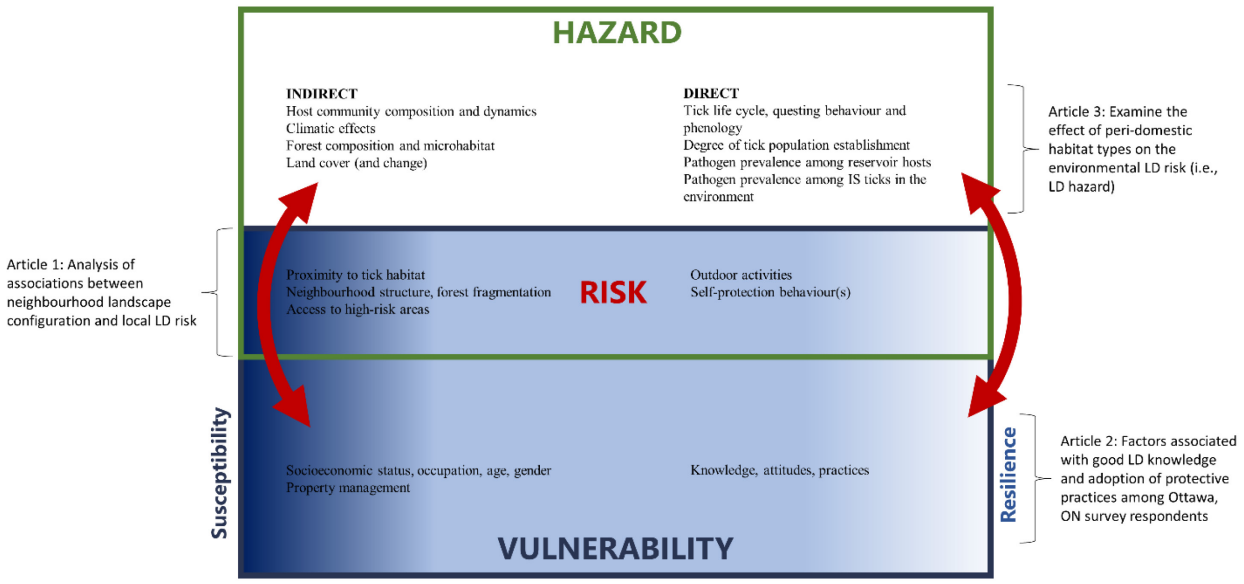


Figure 7.1 Context of thesis articles in the conceptual framework for Lyme disease (LD) risk discussed in Chapter 1.

In this chapter, I synthesize the main results and provide a context for these findings in the existing body of Lyme disease research, particularly as it applies with respect to Lyme disease emergence in Canada. I will further address the general limitations of this work and describe ways to expand on it through future research to further clarify Lyme disease risk amidst the continued climate change-driven establishment and northward progression of its pathogen and vector.

7.1 Unraveling the associations between neighbourhood-level forest indices and Lyme disease risk

In Chapter 4, I presented five models of hypothesized interactions between measures of forested landscape configuration and their associations with the number of Lyme disease cases occurring in Ottawa neighbourhoods. Each of the neighbourhood-level forest indices demonstrated a significant correlation with a higher incidence of Lyme disease resulting from local tick encounters, but two models identified statistically significant interactions with implications for Lyme disease risk at the local scale.

The effect of neighbourhood forest cover (i.e., the interaction between proportion of forest land cover and mean forest patch size) predicted higher local Lyme disease incidence, albeit with a substantially stronger effect where forested proportions remained near the average among Ottawa neighbourhoods. In this case, an Ottawa-average amount of neighbourhood forest comprised of several large patches was associated with very high local Lyme disease incidence. The association present through this interaction weakened under two scenarios: where the forest either dominates the neighbourhood landscape or exists as more fragmented, smaller patches. This supports earlier evidence that fragmenting forests does not have a direct relationship with higher Lyme disease incidence alone [12]. In their twelve-year study of Lyme disease in Connecticut, Brownstein et al. demonstrate that mean patch size and isolation as indices of forest fragmentation predicted greater environmental hazard yet fewer cases of Lyme disease in the same town [12]. The authors' work highlights that the reduction in Lyme disease incidence in the presence of fragmentation does not necessarily contradict the established theory that forest

fragmentation contributes to higher Lyme disease risk [13]. Instead, these results suggest there is more to the integration of forests within towns or neighbourhoods than their size or coverage. Merely accounting for forestation through patch size and coverage measures omits the role of where human activity is most likely to overlap with higher entomological hazard.

The second significant interaction highlighted increased neighbourhood incidence where forest land cover included both larger patches and more complex shapes. Under this scenario, the potential exists for heightened human activity along the forest's edge. In landscape analysis, the association of ecotones with Lyme disease risk has typically been evaluated at regional scales [14]. But, as I highlighted above, considering the presence and integration of forest edge habitat in residential neighbourhoods is crucial for improving our understanding of peridomestic Lyme disease risk. This is supported by the mutual effect of mean forest patch size and edge-to-area ratios observed through their interaction in Ottawa neighbourhoods.

Recent reviews and metanalyses identify disagreement among past studies with respect to the relationship between landscape factors – particularly land use and fragmentation – and Lyme disease risk [14,15]. The explanation posited by Diuk-Wasser et al. is that the supposed contradictions result from differences in spatial and temporal scales of analysis, as well as a need for landscape measurement indices that are contextually relevant to the scale of studied outcome measures [14]. Early studies of landscape effects identified associations between forest land cover or ecotones and a variety of outcomes relevant to Lyme disease [16–20]. However, these analyses focus on predominantly regional and county levels in the United States. More recent studies suggest that land cover variables measured within neighbourhoods are more predictive of

local, peridomestic Lyme disease incidence [15,21]. While the results offered by these differences in scale seem contradictory, they imply an important distinction – scale is particularly relevant in the proper evaluation of Lyme disease risk in a local context. Scale inherently complicates all studies that evaluate landscape associations with Lyme disease risk. Surveillance-based research provides areal estimates of enzootic hazard, aggregating tick densities and any calculated associations. When these results describe associations at a wide scale (e.g., counties, regions), they implicitly attribute risk homogeneously within the study units. For forested landscapes, this suggests the level of risk is consistent in forest interiors and along edges among all forest patches within the study unit. But, as Diuk-Wasser et al. note, the probability of human encounters at forest interior sites is lower compared to ecotonal habitats [14]. Understanding where human activity coincides with tick habitat is vital to estimating risk – as is the scale that best represents this interaction.

We must also consider that the majority of research evaluating the association between Lyme disease incidence and landscape fragmentation comes from the northeast United States. These results stand on the basic assumption that all reported cases result from human-tick encounters that occur within the reporting county [18,22]. This assumes that cases of Lyme disease infrequently result from humans interacting with natural areas outside of their home county. By contrast, in Ontario, exposures in rural communities are typically peridomestic while those experienced by urban and suburban residents tend to follow visits to proximal rural health units [23]. While this would appear to be a mere distinction in risk levels between areas of established and emerging risk, further consideration of the scale of analysis and assumptions of classification is merited. For example, Bisanzio et al. identified a significant relationship between the

proportion of forested area in adjacent counties of the northeastern United States and the predicted probability of Lyme disease cases in the reporting county [20]. Thus, while ecologic studies in any setting cannot account for the local human-driven processes that lead to tick exposure, the size and definition of where and how that exposure occurs must be considered carefully when inferring peridomestic risk.

The modifiable areal unit problem haunts all ecologic studies. It introduces bias when measures are aggregated to imposed geographic units and can significantly affect results when the chosen boundaries are not suitable for the data. This is true regardless of direction. Smaller study units may change patterns observed across the entire landscape but failing to partition information leaves inferences vulnerable to broad generalizations. If we accept that data is represented with bias no matter the chosen scale, we might limit the error introduced by choosing boundaries that reflect the physical geography of local communities at a scale relevant to human activity. For example, a study by Moon et al. compared the associations with Lyme disease incidence detected for percent forest cover and edge density within an 800-metre buffer around residences to the same measures calculated at the broader scale of townships, boroughs, and cities in Pennsylvania [21]. They found that associations with Lyme disease were higher in evaluations of smaller geographic units compared to the wider scales of townships and boroughs. The authors proposed that the residential buffer more closely approximates the lived environment and a more relevant spatial context for peridomestic Lyme disease risk. While I focused on larger geographic boundaries than the residential buffer, my results provide additional evidence that well-defined communities such as the ‘natural neighbourhoods’ defined by the Ottawa Neighbourhood Study represent a spatial scale ideal for estimating local risk.

In the Canadian context, my thesis presents the first study in an area of emerging Lyme disease risk to explore relationships between peridomestic disease incidence and characteristics of forestation in the immediate neighbourhood. While this was an ecologic analysis with outcomes and measurements aggregated to neighbourhood boundaries, the results merit further investigation at local scales where patient exposure data can be connected to peri-urban woodlands and observations of fine-scale blacklegged tick densities. It is difficult to connect Lyme disease case data to the area of exposure reliably and with precision, though projects that leverage mobile applications for citizen science data continue to improve the spatial attribution of tick exposures, particularly in endemic regions [24,25].

7.2 Understanding factors associated with Lyme disease knowledge and adoption of preventive behaviours

To truly understand local Lyme disease risk, it is crucial to discern the extent that individuals in the community are vulnerable. In Chapter 5, I reported results from a cross-sectional survey of Ottawa adults gauging the population-level susceptibility to and resilience against tick exposure and transmission of *B. burgdorferi*. While Ottawa, Ontario was deemed an at-risk region in 2017, the presence of blacklegged ticks is still heterogeneously distributed across areas otherwise deemed suitable habitat for their survival and colonization [10,26,27]. In such regions of blacklegged tick emergence, a lag in risk perception exists between local hazard, public awareness of Lyme disease risk, and the adoption of protective or preventative actions taken by individuals. Thus, with clustered spatial detection of host-seeking tick activity, it is important to

identify the factors that characterize patterns of awareness and protection amongst populations in this setting.

My thesis provides important context into the degree to which adult Ottawa residents are knowledgeable about Lyme disease and how well they protect themselves. In the surveyed sample, 60% of respondents correctly answered at least four of the five questions about Lyme disease. Crucially, 85% of all respondents knew that Lyme disease occurs in humans following a tick bite. No significant differences in knowledge level were present between the city region strata used in our sampling design, though respondents with a yard had 1.6 times higher odds of having high Lyme disease knowledge. This increased to 2.5 times higher odds of high knowledge if the individual was personally responsible for their yard's maintenance. A connection between tick-borne disease awareness and rurality is well-established in the United States and Canada [28–30]. This relationship is natural, given the geography of rural environments – a greater distance between human residences, with the opportunity for suitable tick habitat interspersed – contributes to many cases resulting from peridomestic tick exposures [23,30]. In this region of emerging risk, my results suggest an association between yard access and higher odds of good Lyme disease knowledge independent of rurality. Further, the clusters of local Lyme disease cases I identified through preliminary analyses and the neighbourhood incidence of local cases observed in Chapter 4 (Figure 7-2) are indicative of a high occurrence of local risk in the western suburbs of Ottawa between 2017 and 2020 and appear to support the trend in suburban local risk which can precede raised public awareness.

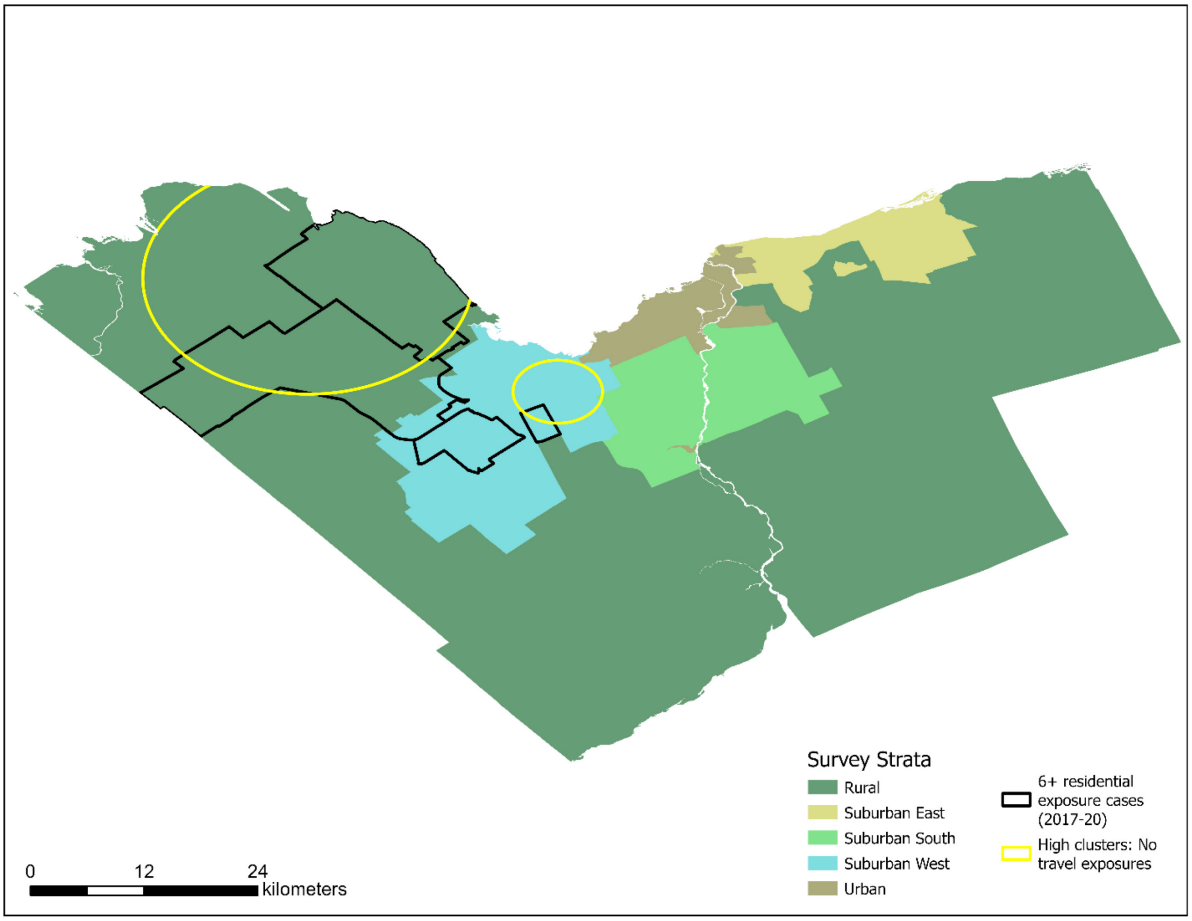


Figure 7.2 City region strata definitions used in KAP survey recruitment. ONS neighbourhoods with greater than 5 locally-acquired cases between 2017 and 2020 are outlined in black. The area covered by clusters with high incidence of local cases is identified in yellow.

With respect to sociodemographic characteristics, my results highlighted differences between population subgroups with respect to Lyme disease knowledge and the adoption of protective practices. Significantly, non-Indigenous racialized respondents were less likely than White respondents to be aware of how Lyme disease is transmitted or treated yet nearly twice as likely to adopt a high number of measures to protect themselves. A similarly discernible difference in the level of perceived risk expressed by respondents from these population groups was not

present in the collected responses. Between these subgroups, the adoption rate of specific measures – wearing insecticide-treated clothing, using pesticides on their lawn, or avoiding the woodlands entirely – was significantly greater among non-Indigenous racialized respondents. There are unmeasured factors influencing these differences which I detail further below, but these results encourage further research into the motivating links between knowledge and actions to protect against Lyme disease. By comparison, when controlling for other characteristics, good knowledge regarding Lyme disease was more likely from members of older age groups and in women compared to men. Yet neither age nor gender held a significant association, positively or negatively, with the adoption of a high number of protective practices.

In Chapter 4, I noted that nearly two-thirds of Lyme disease cases reported to Ottawa Public Health attributed their exposure to travel outside of the municipal region. Slatculescu et al. also highlight that, during the period from 2010 to 2017, patients from urban regions of eastern Ontario most frequently reported their exposure occurred in neighbouring rural health units [23]. A novel aspect of my thesis was asking survey respondents to identify (up to three of) the "wooded areas or areas with tall grass and/or shrubs" that they visited most often during the tick risk season of May to October. Understanding this aspect of vulnerability in the local community is especially important in an area with emerging Lyme disease risk like Ottawa, given differential perceptions of local environmental risk across the city. By asking respondents to identify the wooded locations they visit and identifying generally how far from their home these sites are, I identified population-level patterns of activity that represented elevated susceptibility. In this sample, 82% of respondents indicated they frequently visit a site with high estimated environmental Lyme disease risk, travelling an average of 15.4 kilometres from their home. Of

this group, those who frequented wooded areas more than 10 times between May and October had 40% to 70% higher odds of demonstrating high knowledge regarding Lyme disease yet 30% to 50% lower odds of adopting a high number of practices to protect themselves compared to those in the negligible exposure risk category. This evidence highlights an opportunity to strengthen public health messaging regarding environmental Lyme disease risk throughout the region with an emphasis on the need to adopt multiple protective behaviours.

7.3 Fine-scale characterization of Lyme disease hazard and implications for disease risk

Through my third objective, I presented the result of two years of field surveillance for the vector and pathogen of Lyme disease at a fine scale in four neighbourhoods of western Ottawa, Ontario. The aim of this project was to establish the level of risk across the residential-woodland ecotone (or the "interface" zone, as conceived for this project) in neighbourhoods known through previous surveillance activity to possess high environmental Lyme disease risk [10,31]. We achieved a high temporal (intended to be every two weeks, but monthly during the COVID-19 Pandemic) and spatial (50-metres-squared rectangular quadrats) resolution for observations through a rigorous sampling approach. Conducted between May and October of both years, this approach ensured we would sample during the peak period of activity for each tick instar – early summer months for nymphs, late summer for larvae, fall and the following spring for adults [32–34]. We collected adult or nymphal blacklegged ticks from all zones except the residential zone of N1 across the 36 sites from the four study neighbourhoods.

In Chapter 6, I showed that a distinct gradient of Lyme disease risk is present as one progresses from residential habitats through the ecotonal area and further into woodlands. My results

leveraged a conceptual model informed by the influence of site-level characteristics of the microhabitat on tick survivability as well as the zonal abundance of preferred hosts (i.e., white-footed mice and white-tailed deer) on vector density and infection prevalence. While the initial intent was to analyze the densities of nymphal ticks and infected nymphal ticks, the sample size and failure to detect nymphal infection in some of the neighbourhood zones resulted in singular model fits for the latter outcome. However, the observed and estimated infection prevalence of nymph and adult ticks combined (i.e., the stages capable of transmitting *B. burgdorferi* to humans) highlight the need for continued high-frequency active surveillance in these locations. This is particularly true since the data collection and analysis spans only one iteration of the tick's multi-year lifecycle. With a longer study period overall and precision of repeated environmental measurements, additional temporal lags may explain some of the differences in observations between the tick instars. As these models controlled for microhabitat characteristics of sampling sites and the zonal abundance of hosts, the zonal risk I estimated points to real human Lyme disease risk in ecotonal areas between residential properties and peri-urban woodlands – highlighting the need for targeted interventions and clear public health messaging strategies in similar communities.

Past studies paint contrasting depictions of associations between forest edge habitat and Lyme disease risk because they tend to focus exclusively on the role of *I. scapularis* ticks or specific hosts in entomological hazard. Tick abundance and *B. burgdorferi* infection prevalence is frequently greater in woodlands than in wooded edges [35,36], though evidence of greater densities of *I. ricinus* ticks in edge habitat compared to woodland interiors exists [37–39]. White-footed mice also show a strong preference for the interior of forested areas [40,41], though this

may depend on the size of forest patches and the configuration of the landscape [42]. However, these interpretations focus on the differences between forest interiors and the ecotone shared with open habitat or herbaceous landcover (e.g., fields, parks). My findings suggest that the ecotone between forests and residential properties is an equally critical habitat. Recognizing these areas as presenting the most likely opportunity for human activity and host-seeking ticks to interface, researchers have begun to examine their contribution to human Lyme disease risk at both the landscape [20,43] and local [44–46] levels, though it remains understudied compared to ecotones between woodlands and open areas. Crucially, a "One Health" approach that specifically estimates the enzootic hazard between backyards and local forests is missing to date.

7.4 General limitations and future research

7.4.1 Ecologic studies for landscape effects on Lyme disease risk

Evaluations of landscape associations with Lyme disease risk are, by necessity, ecologic studies. While this form of study design is incapable of producing inferences on individual cases from aggregated data, it is particularly well-suited to identifying the role of landscape effects in the hazard component of vector-borne disease etiology. Over time, the focus of these Lyme disease study designs has shifted from estimations of the amount of landscape forest cover to quantifying forest fragmentation. In Chapter 2, I established that studies performing ecologic assessments of risk do so at a variety of spatial scales and resolutions. Given that the inference in these cases is about the nature of the landscape and not individuals in the community, it allows for generalizations about the environmental risk present in the studied area, provided that exposure to the vector of disease or, human encounters with blacklegged ticks, occurs as a result of the inferred hazard. This is based on two key assumptions: first, the estimated environmental risk is

presumed to be homogeneous to all habitats across all geographic units at the chosen scale; and second, all the reported cases resulted from exposure inside of these study units. This may be a safe set of assumptions in regions like the northeast United States, which exhibits long-established endemicity of the Lyme disease pathogen and vector in most settings. During the ongoing northward range expansion of blacklegged ticks, heterogeneity in the environmental risk for Lyme disease in regions of emerging risk like Canada means it is difficult to rely on these assumptions in evaluating landscape effects [23,47].

I mitigated this with two main strategies. I reduced the chance that error was introduced through the erroneous assumption that risk is spatially homogeneous by using smaller geographic areas as my study units. While the use of any geographic boundaries is subject to the modifiable areal unit problem, these areas were specifically defined by their characterization of distinct neighbourhoods [48]. I also used case inclusion criteria that restricted analysis to those that declared the most likely site of their tick encounter was the same as their home address or within their home neighbourhood boundary. It is possible that some cases were misclassified as local exposures, but there is no reason to believe that recall and self-reporting accuracy of tick encounter locations is any different in Ottawa, Ontario than in other regions with high environmental Lyme disease risk. As most cases reported to Ottawa Public Health experienced their tick encounter during travel outside of the city, this criterion ensured that only cases with likely attribution to the neighbourhood were counted. Across Ottawa, the spatial distribution of cases defined as ‘local’ echoed the pattern of sites where recent surveillance activity identified high tick densities [10] and supports the observation that, in settings across Ontario, peridomestic

exposures occur in rural regions while residents from urban areas are typically exposed during visits to rural surroundings [23,49].

I also did not identify specific edge contrasts, such as neighbourhood differences in woodland edges shared with residential, agricultural, or open area land covers, that would convey relative ecotonal associations with local Lyme disease. Still, the indices I used were calculated at a scale well-suited to identifying correlations between overall forest configuration and peridomestic risk. Numerous studies document the influence of the wildland-urban interface in predicting Lyme disease risk at regional scales in the United States [14,16–18]. Yet, as different geographic scales are explored, there is mounting evidence that evaluating the balance of forestation and human habitation in local neighbourhoods is generally more predictive of local risk [15,21,50]. However, the majority of this evidence focuses on areas where macro-scale patterns of risk are generally homogeneous and a majority of the human population resides within the wildland-urban interface. Given that Lyme disease hazard is still emerging in Ontario, a local scale of analysis allows for the identification of differences across the landscape – even with generalized definitions of fragmentation patterns – due to the heterogeneity of established tick populations across this region. In future research, analysis based on more discrete ecotonal definitions may further refine these estimates.

7.4.2 Estimating vulnerability components with survey results

One of the key aspects of vulnerability I explored through my analysis of KAP survey results was the degree to which respondents protect themselves against Lyme disease. I addressed this by identifying factors associated with ‘high’ personal protection, defined as “always” or

"frequently" adopting 5 to 7 practices. This definition serves as a population-level estimate of Ottawa adults who follow the 'Swiss cheese' metaphor proposed by Reason [51] for personal safety. That is, these individuals exhibit a high level of resilience by using multiple practices intended to prevent personal exposure and risk in concert, with each individual practice hopefully covering for the weaknesses – or holes – in the others. One limitation of this analytical approach is a gap that occurs frequently in behavioural studies of Lyme disease protection: while we identified the usage rates of specific protective behaviours, we did not ask respondents to identify what specific combinations of practices they adopt, or if they adopt one or several knowingly at the exclusion of others [52]. This is a general limitation of the KAP approach, as the survey design does not include open questions and is thus not well-suited to identifying behavioural motivations. Further research, ideally leveraging qualitative or mixed methods (e.g., interviews, focus groups) would help clarify this behavioural tendency. However, these results emphasize an opportunity might exist in specifically stressing the 'Swiss cheese' metaphor for protection in this context.

Another finding from this analysis that merits more detailed exploration is the dissociation between Lyme disease knowledge and personal protection among non-Indigenous racialized respondents. In Chapter 5, I feature that this group demonstrated decreased odds of high knowledge while also having an association with greater odds of significant adoption of protective measures compared to White respondents. Our survey instrument failed to capture recent immigration to Canada as a characteristic of all respondents, though there is the potential that this is differentially represented in this population group. We asked how long respondents had lived in Ottawa, but lacked the ability to infer how long any respondent was resident in

Canada. The higher rate in avoidance of woodlands I observed among this population subgroup could be as attributable to differences in recreational preferences as to recent immigration status. It would also be an error to assume any new residents of Ottawa relocated from an area with widely-known Lyme disease endemicity, therefore narrower questioning on the duration of residence in Canada and Ottawa, how long the respondent has known about blacklegged ticks and/or Lyme disease, and whether this knowledge factors into avoidance of woodland areas would aid further research into these aspects of vulnerability to Lyme disease.

7.4.3 Analysis of ecological effects between residential, interface, and woodland zones

While the estimates I calculated for zonal effects on tick density and infection prevalence in the studied neighbourhoods are based on surveillance activities conducted with high temporal and spatial resolution, the total sampling period (2019-2020) covered only two years. Even with the high sampling frequency used in this study, tick distributions exhibit complex spatiotemporal heterogeneity that affects tick detection in between-site comparisons [32,53]. As Dumas et al. note [32], sampling in a single location within a municipality may not accurately represent the tick hazard for the whole area. Thus, several possibilities for low detection rates exist. For one, the degree of *I. scapularis* invasion in several of these neighbourhoods may not have progressed as far as hypothesized. Second is that specific characteristics of some sampled sites may make them less ideal for tick survival compared to others. Lastly, while the initial study design featured biweekly sampling in both years, we were required to abbreviate our first surveillance season to monthly efforts due to local COVID-19 restrictions. At either frequency, the detection of ticks can be sensitive to daily variations in heat, humidity, and recent precipitation [54]; these results

might be different if surveillance activities occurred on different days or times. Given the scope of the surveillance activity needed to make zonal inferences, the sampling protocol we used was necessary to minimize cost and efficiently allocate resources. Still, the presence of multiple stages detected at a fine scale represents evidence that established and reproducing populations of *I. scapularis* ticks are present. Since Lyme disease is still in an emergent stage in this region, the 2-year time scale of our sampling effort does not allow us to infer spatial and temporal differences in the activity of blacklegged tick instars. It is necessary to have sampling locations with expected non-detection in the data to arrive at valid associations, but continued research with an expansion of monitored sites is warranted to substantiate these findings. Enhanced longitudinal surveillance over additional sites is necessary to make conclusions regarding the local patterns in the blacklegged tick life cycle.

We also did not account for the structure or diversity of the broader vertebrate host community among our considerations of the influence potential hosts might play in modelling the tick infection prevalence. I should note that this is not explored extensively in the literature in general [55], as most studies focus cross-sectionally on a genus (as we did with *Peromyscus*-species mice) or specific species presumed to be the most competent pathogen reservoir to estimate environmental risk. Yet the theoretical models underpinning the dilution and amplification effects for disease risk stress the need to consider local biodiversity and thus gain insight into transmission dynamics that impact environmental risk. For example, Werden et al. showed that a lower density of infected nymphs at sites of Ontario's Thousand Islands Archipelago was associated with higher species richness yet was still driven by the relative abundance of *P. leucopus* mice [56]. In Québec, another area of Lyme disease emergence, Millien et al. also

report an influence of small mammal community composition on *B. burgdorferi* infection prevalence in tick vectors [57]. This is especially relevant in studies at a high spatial scales that focus on edge habitat, where dynamics like competitive displacement in small mammal communities may cause more variation [58]. While a focus on white-footed mice is necessary for estimates of *B. burgdorferi* prevalence in the environment, further research could benefit from collecting data on the distribution and relative abundance of small mammal populations, gaining insight into the intensity of transmission cycles in local settings.

An initial, proposed intent for this study was to process and analyze PlanetScope satellite imagery for the study zones in this objective as they were used in the analysis presented in Chapter 4. However, the surveilled areas were part of larger forest complexes rather than independent forest patches. The landscape observations used in the earlier objective represent generalizations of the local forest fragmentation for the neighbourhood as a whole. After working with the available imagery obtained for neighbourhood analyses, I determined that the site-specific characteristics, while point-based observations, were more appropriate for the scale of analysis than the landscape-level measurements derived earlier. Moreover, the observations of leaf litter we used in estimation of the microhabitat are not very precise – only one point estimate was taken, rounded to the nearest centimetre, to represent 50-square-metre sampling locations. This approach may introduce rounding errors, and resulted in binned categories as more appropriate for the data available, even though this has less power in statistical inference than if it were continuous. The use of generalized woodland characteristics for a study site to predict tick abundance is a common approach for ecological observations [59], but these may be vulnerable to observer bias, ecological fallacy, or both. A granular accounting for forest composition would

be better achieved via fine-scale forest inventories, such as could be achieved through Unmanned Aerial Vehicle (UAV) photography and itemizing information within images via trained machine learning processes. This type of ecological data collection for the whole habitat would provide improved estimates not only of tree species composition and distribution, but also estimated accumulation of leaf litter, as inventory-based data would provide information on the relative abundance of tree species with dense canopy and generate litter that serves as ideal shelter for tick survival (e.g., maple, birch, oak, etc. [59]).

7.5 Implications for Public Health

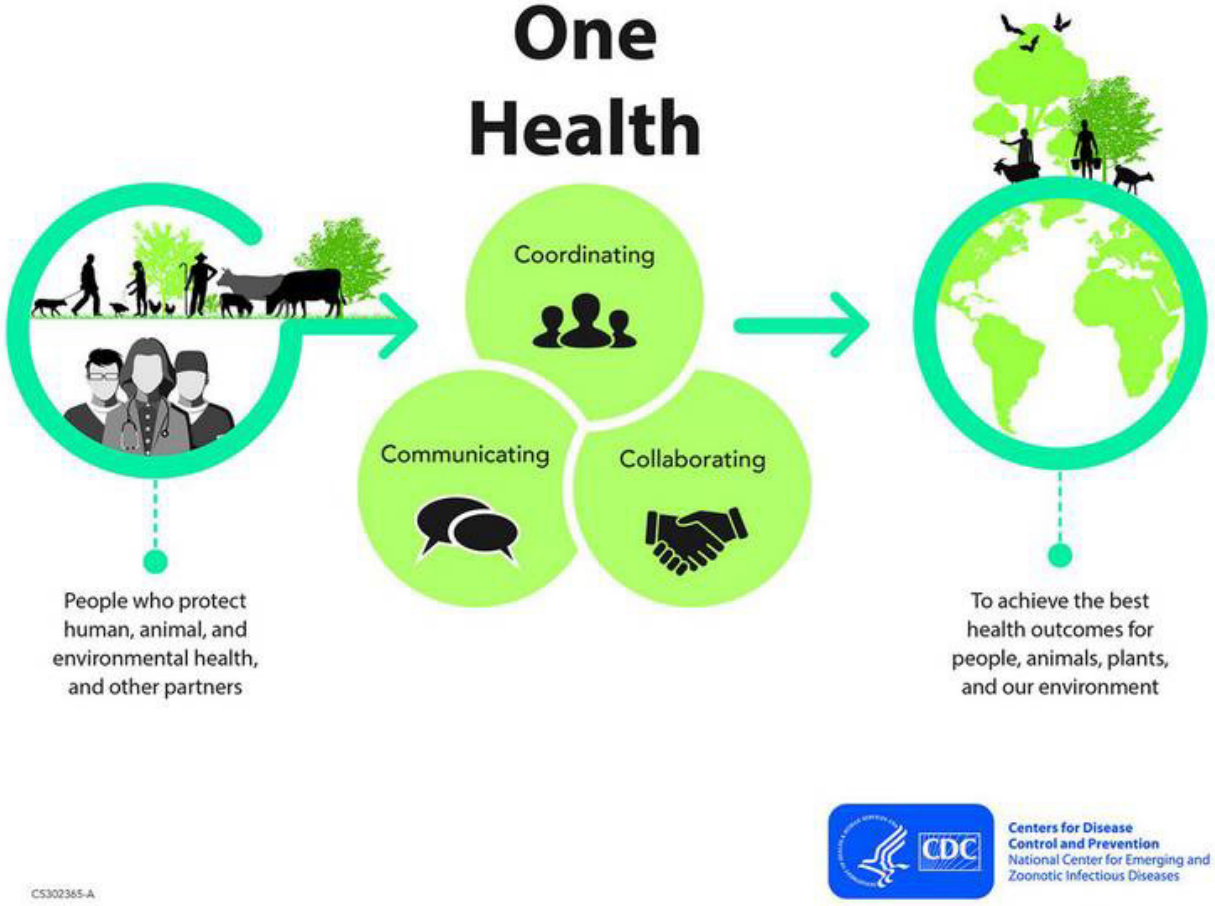
The results presented in this thesis fill critical knowledge gaps regarding how we understand emerging Lyme disease risk in a local setting through the lenses of hazard and vulnerability. I have cited the heterogeneity in spatial extent and advancement of *I. scapularis* colonization in the Canadian setting frequently above. Rural areas are the bellwether for risk emergence across the region, through the greater likelihood of cases due to peridomestic exposures and those resulting from activities of urban residents in these areas. But, suburbs and peri-urban areas are most directly affected by the simultaneous changes via urban expansion and the ecological processes driving tick population spread. Thus, human habitation and activity in these communities has the potential to intersect more frequently with suitable tick habitat where the vector's density is increasing. My work conveys key insights in how this heterogeneity manifests as Lyme disease risk across the urbanization gradient that can be used to reduce the public health threat of Lyme disease through urban design guidelines, intervention measures, and community messaging.

First, my neighbourhood-based analysis and peridomestic incidence maps of the Ottawa municipal region are a valuable resource for public health officials. I also provide the first fine-scale evaluation of environmental Lyme disease risk across the residential-woodland gradient through a multi-year assessment of settings with the highest local incidence. Though this analysis, I provided evidence of the environmental risk present in the ecotonal interface between residential backyards and woodlands integrated into the community. Together, these findings supplement prior evidence that local risk is rising with the establishment of blacklegged tick populations in suitable habitat in various communities of the Ottawa municipal region. Furthermore, the map of peridomestic incidence demonstrates that peridomestic cases occur in the southern and eastern neighbourhoods of the municipality. Though the possibility exists that some of these cases may result from encounters with adventitious ticks, it hints that ongoing emergence will not remain contained to the west. Continued active surveillance and targeted messaging will benefit all peri-urban communities while local incidence of Lyme disease is still comparatively low.

In my characterization of Lyme disease vulnerability among Ottawa residents through their knowledge and personal protection, I identified critical gaps and opportunities that can support stronger public health communication. Though my findings suggest that awareness and general knowledge of blacklegged ticks and Lyme disease is generally good - 85% are aware it Lyme disease occurs in humans due to tick bites and 93% believe it to be a very serious disease – just over half of respondents are personally concerned with being infected. This critical gap between awareness and risk perception, coupled with the 50% lower odds (95%CI: 0.30, 0.80) of adopting a high number of protective practices among respondents considered to have a high exposure

risk, presents opportunities for targeted messaging. For example, strong knowledge levels appear to be characteristic of both residents with yards as well as those who frequently visit wooded areas with potential for high environmental risk, yet the latter group is much less likely to exhibit strong protection behaviours. The use of this information can help to improve cost-efficiency and targeted outreach of public health communication in the community.

Conducting this research in Ottawa, a municipal region designated as at-risk for Lyme disease during the last seven years, these findings can be used to prepare intervention and communication strategies for residents of other communities in advance of projected blacklegged tick emergence. Under the One Health context observed across this work, coordination, collaboration, and engagement with the community is integral to achieving optimal health outcomes for humans, animals, and the environment (Figure 7.3). This must remain in focus as municipalities like Ottawa change our landscape with urban development and greening projects. Through these changes, we will continue to alter the environment in ways that invite increased interaction between human activity and areas of Lyme disease hazard. Research must continue to improve our understanding of how factors related to humans, wildlife, and the environment are associated with local Lyme disease transmission cycles. Interactions among these elements all contribute to the rise in risk. But, truly adopting the One Health approach involves continued engagement between stakeholders – individuals, their communities, and policy-makers – with locally relevant evidence that can be used to communicate and mitigate risk.



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4934 **Figure 7.3** Infographic generated by the Centers for Disease Control and Prevention to explain the
4935 processes necessary in achieving a One Health approach [60].

4936

4937 **7.6 Conclusions**

4938 Areas experiencing the emergence of blacklegged tick populations pose a particular challenge to
4939 measuring Lyme disease risk. Specifically, regional understanding of the environmental risk of
4940 Lyme disease does not necessarily translate into immediate concerns for residents in local
4941 peridomestic settings. The heterogeneity of tick populations and infection prevalence at finer
4942 spatial scales contributes to an uneven comprehension of local risk and the necessary actions for

personal protection. My thesis combined interdisciplinary methodologies to evaluate risk as a function of Lyme disease hazard and vulnerability in the Ottawa, Ontario region. By studying the components of this conceptual model during the same period of time, I gleaned a current, practicable impression of local risk that can inform (1) public health intervention and control measures; and (2) ongoing research efforts whose aim it to monitor the geographic expansion of risk across this region. Through an ecological study of local Lyme disease cases, I used remote sensing imagery and spatial analysis methods to demonstrate the utility of identifying associations between factors representing landscape configuration at the neighbourhood level and Lyme disease risk. This work confirms earlier evidence of the increasing threat of domestic tick exposure and Lyme disease transmission in peri-urban Canadian environments.

In my Ottawa-based analysis of aspects associated with Lyme disease vulnerability among respondents, Lyme disease awareness was high, while good adoption of protective measures was low. This was particularly true of individuals who are responsible for maintaining a yard. While I did not identify significant differences in these outcomes between city region strata, access to and responsibility for an outdoor yard are more characteristic of suburban and rural neighbourhoods of Ottawa. Prior evidence, supported by the findings of my previous objective, indicates peridomestic exposures are much more prevalent in these environments. Yet awareness and local perception of Lyme disease hazard appeared to be insufficient to drive good adoption of protective behaviours. I found that respondents who visit high-risk wooded areas most frequently were significantly less likely to adopt 5 or more behaviours intended to protect themselves against Lyme disease.

My thesis also provides evidence that the ecotone, or 'interface,' between residential properties and woodlands holds significant Lyme disease transmission risk. Understudied in Canada, dynamics in this interface habitat require improved understanding as the setting where interaction between host-seeking tick populations and human activity is most likely. I identified an association between Lyme disease risk and the peri-urban interface habitat that requires further research as improved understanding may enhance urban design guidelines, public health communication efforts, and integrated tick interventions in these settings. These findings should be confirmed through continued surveillance in these and additional neighbourhoods; improved sample sizes through longitudinal studies of the same areas might validate and refine the estimated associations we detected in only two years of sampling. Since tick population establishment and activity can be heterogeneous even at this scale, it is important to expand this research to suitable tick habitat in neighbourhoods where presence is presumed but not yet detected or detected with low density.

In conclusion, my thesis emphasizes the necessity for continued action on two fronts with respect to local Lyme disease risk. First, the establishment and maintenance of active surveillance schedules in peri-urban Canadian settings are important while geographic distributions of blacklegged tick populations are highly heterogeneous across regional landscapes. Second, evidence from these activities should be used to tailor public health messaging and to target environmental Lyme disease control interventions. Individually, the research objectives covered in this thesis suggest that identifying local patterns will help focus these activities on high-risk sections of communities, improving the cost and efficiency of these measures. Continued

understanding of the fine-scale influences of Lyme disease hazard and vulnerability will aid overall risk reduction as the threat of Lyme disease emergence continues in Canada.

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Appendices

A. Appendices to Chapter 4

A1. Open access availability of data sources, provided to PLoS ONE

Data Description	**Date range**	**Data format**	**Source**	**URL**	**Licence**
Lyme disease surveillance data Annual surveillance data of Lyme disease cases reported to Ottawa Public Health, including age, sex, date of disease onset, address, and five locations identified as the site of suspected tick exposure	2017-2020	Table, CSV	Public Health Information System (iPHIS) of Public Health Ontario	Ottawa Public Health	Data Sharing Agreement
Neighbourhood boundaries Boundaries created by the Ottawa Neighbourhood study to analyse population statistics.	November 25, 2019	Polygon shapefile (.SHP)	Ottawa Neighbourhood Study (ONS)	Open Data Ottawa	Open Government Licence - Canada v2.0
Neighbourhood statistics of social determinants Socioeconomic and demographic variables selected from the Statistics Canada census and calculated within ONS-delineated boundaries (e.g., median household income, population estimates)	2016	with above	Statistics Canada, ONS	Ottawa Neighbourhood Study	*Statistics Canada Open Licence*
Land Imagery 38 images selected from daily 4-band multispectral satellite data and mosaicked into one high-resolution image of Ottawa. The land classification generated from a mosaic of PlanetScope satellite imagery	August 2018	TIF 3.7 m resolution	PlanetScope	Website of imagery products: Planet Labs PBC Classification: uOttawa Dataverse	Education and Research program End User Licence Agreement CC BY 4.0

B. Appendices to Chapter 5

B1. FSAs included in neighbourhood strata definitions

Stratum	FSA
Urban	K1H
	K1L
	K1M
	K1N
	K1P
	K1R
	K1S
	K1Y
	K1Z
	K2A
	K2B
	K2C
	K2P
Suburban East	K1B
	K1C
	K1E
	K1J
	K1K
	K1W
	K4A

Suburban West	K2H
	K2K
	K2L
	K2M
	K2R
	K2S
	K2T
	K2V
Suburban South	K1T
	K1V
	K2E
	K2G
	K2J
Rural	K0A
	K0G
	K1G
	K1X
	K2W
	K4B
	K4C
	K4M
	K4P
	K7S

B2. Survey Instrument

Survey of Lyme Disease Knowledge, Attitudes and Practices

November 2020 - INSIGHT Research Lab / Leger Opinion

Data Dictionary

Age (LEO)

0	Under 18
1	Between 18 and 24
2	Between 25 and 34
3	Between 35 and 44
4	Between 45 and 54
5	Between 55 and 64
6	Between 65 and 74
7	75 or older
9	I prefer not to answer

Region

1	Suburban East
2	Suburban South
3	Suburban West
4	Rural
5	Urban
6	Other

Q35. What is your gender

1	Woman
2	Man
3	Non-binary/third gender
96	Prefer to self-describe
99	I prefer not to answer

Q35r96oe. What is your gender – Self description field

Open response question

Q37. Do you identify as an Aboriginal person, that is, First Nations, Métis or Inuk (Inuit)?

1	Yes

2 No
3 I prefer not to answer

Q38. Which population group do you belong to?

0 Unchecked
1 Checked
Q38r1 White
Q38r2 South Asian (e.g. East Indian, Pakistani, Sri Lankan, etc.)
Q38r3 Chinese
Q38r4 Black
Q38r5 Filipino
Q38r6 Latin American
Q38r7 Arab
Q38r8 Southeast Asian (e.g. Vietnamese, Cambobian, Laotian, Thai, etc.)
Q38r9 West Asian (e.g. Iranian, Afghan, etc.)
Q38r10 Korean
Q38r11 Japanese
Q38r96 Other
Q38r99 I prefer not to answer

Q38r96oe. Which population group do you belong to? – Other

Open response question

Q39. What language do you speak most often at home:

1 English
2 French
3 Both English and French equally
96 Other
99 I prefer not to answer

Q39r96oe. What language do you speak most often at home – Other

Open response question

Q40. What is the total before-tax income of all household members for 2019?

1 $19,999 or less
2 Between $20,000 and $39,999
3 Between $40,000 and $59,999
4 Between $60,000 and $79,999
5 Between $80,000 and $99,999
6 Between $100,000 and $119,999
7 $120,000 or more

9 I prefer not to answer

Q41. What is the highest level of education you have completed?

1 Primary (elementary school)
2 Secondary (high school)
3 College (technical training and/or certificate)
4 University: graduate certificate and/or diploma
5 University: undergraduate degree (Bachelor's)
6 University: graduate degree (Master's)
7 University: graduate degree (Doctorate)
96 Other (specify)
99 I prefer not to answer

Q41r96oe. What is the highest level of education you have completed – Other

Open response question

Q1. How long have you lived in Ottawa?

1 Less than a year
2 1 to 5 years
3 6 to 10 years
4 More than 10 years
9 I prefer not to answer

Q2. Lyme disease is transmitted to humans:

0 Unchecked
1 Checked
Q2r1 By contact with rodents
Q2r2 By contact with an individual
Q2r3 By contact with an infected dog
Q2r4 By a tick bite
Q2r5 By a mosquito bite
Q2r9 I do not know
Q2r99 I prefer not to answer

Q3. The best way to remove a tick attached to your skin is:

0 Unchecked 1
Checked

Q3r1 Pull it out with tweezers/forceps/tick remover/other tool
Q3r2 Apply heat, salt or alcohol to the area with the tick
Q3r3 Pull/flick/pick it off using your hand

Q3r96 Other

Q3r98 Don’t know/not sure

Q3r99 I prefer not to answer

Q3r96oe. The best way to remove a tick attached to your skin is – Other

Open response question

Q4. The first symptom of Lyme disease is usually:

0 Unchecked

1 Checked

Q4r1 Diarrhea

Q4r2 Vomiting

Q4r3 Cough

Q4r4 Headache

Q4r5 Fever

Q4r6 A reddish rash on the skin

Q4r7 Lethargy/malaise

Q4r8 Nasal congestion

Q4r98 I do not know

Q4r99 I prefer not to answer

Q5. When detected quickly, Lyme disease can be treated:

0 Unchecked

1 Checked

Q5r1 With antibiotics in tablet form

Q5r2 With creams applied to the skin

Q5r3 With cough medicines

Q5r4 There is no treatment for Lyme disease but a preventive vaccine exists

Q5r5 There is no treatment or vaccine against Lyme disease

Q5r8 I do not know

Q5r9 I prefer not to answer

Q6. In Ottawa, it is possible to contract Lyme disease:

0 Unchecked

1 Checked

Q6r1 Only in wooded areas

Q6r2 In some wooded areas including public access parks

Q6r3 In urban areas

Q6r4 In residential areas

Q6r5 With current scientific knowledge, it is not known if it is possible to contract Lyme disease in Ottawa

Q6r6 It is not possible to contract Lyme disease in Ottawa now

Q6r8 I do not know
Q6r9 I prefer not to answer

Q7. During the past spring or summer, would you say you are at high risk, medium risk, or no risk of getting Lyme disease?

1 High risk
2 Medium risk
3 Low risk
4 No risk
8 Don't know / not sure
9 I prefer not to answer

Q8. Lyme disease is a very serious disease:

1 Totally agree
2 Somewhat agree
3 Neither agree or disagree
4 Somewhat disagree
5 Strongly disagree
9 I prefer not to answer

Q9. It would be easy for me to protect myself against Lyme disease:

1 Totally agree
2 Somewhat agree
3 Neither agree or disagree
4 Somewhat disagree
5 Strongly disagree
9 I prefer not to answer

Q10. I have the feeling that there are great scientific uncertainties about Lyme disease:

1 Totally agree
2 Somewhat agree
3 Neither agree or disagree
4 Somewhat disagree
5 Strongly disagree
9 I prefer not to answer

Q11. I am worried about the idea of contracting Lyme disease:

1 Totally agree
2 Somewhat agree
3 Neither agree or disagree
4 Somewhat disagree
5 Strongly disagree
9 I prefer not to answer

Some measures can help prevent Lyme disease. If the following measures were effective AND technically feasible, please choose the options you would consider most acceptable (that it aligns with your personal values and principles). The following measure respects my personal values and principles:

Q12Q20r12. Apply pesticides to the environment to reduce the presence of ticks knowing that nontarget species would be killed as well

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Q12Q20r13. Use biological control techniques in the environment to reduce the presence of ticks (for example, putting fungi into the environment that can reduce ticks)

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Q12Q20r14. Removing vegetation in forested areas to reduce tick numbers

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Q12Q20r15. Placing woodchip borders along trails in public access woodlands to reduce tick numbers

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Q12Q20r16. Protect deer against ticks using feeding stations that apply a topical pesticide to the deer to reduce tick numbers

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Q12Q20r17. Controlling the number of deer in public access woodlands to reduce the number of ticks

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Q12Q20r18. Prevent deer from visiting publicly accessible woodlands by putting barriers to reduce the number of ticks

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Q12Q20r19. Protect small rodents against ticks using baited traps that apply a topical pesticide to reduce the number of infected ticks

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Q12Q20r20. Vaccinate small rodents to protect them against the bacteria that causes Lyme disease to reduce the number of infected ticks

1 Totally acceptable
2 Fairly acceptable
3 Neither acceptable or unacceptable
4 Fairly unacceptable
5 Totally unacceptable
9 I prefer not to answer

Please identify the measures you currently use to protect yourself from Lyme disease. In Ottawa, I apply this measure to protect myself from Lyme disease:

Q21Q27r21. Seeking and removing ticks on yourself after a stay in a forested area

1 Always
2 Frequently
3 Rarely
4 Never
5 Sometimes I apply this measure, but not to protect myself from Lyme disease
6 Does not apply to my situation
9 I prefer not to answer

Q21Q27r22. Wearing long clothes that covers the legs (for example, tuck pants into socks)

1 Always
2 Frequently
3 Rarely
4 Never
5 Sometimes I apply this measure, but not to protect myself from Lyme disease
6 Does not apply to my situation
9 I prefer not to answer

Q21Q27r23. Use insect repellants with DEET or Icaridin on skin and / or clothing

1 Always
2 Frequently
3 Rarely
4 Never
5 Sometimes I apply this measure, but not to protect myself from Lyme disease
6 Does not apply to my situation
9 I prefer not to answer

Q21Q27r24. Wear clothing treated with an insecticide (e.g. permethrin or InsectShield)

1 Always
2 Frequently
3 Rarely
4 Never
5 Sometimes I apply this measure, but not to protect myself from Lyme disease
6 Does not apply to my situation

9 I prefer not to answer

Q21Q27r25. Avoid woodlands during the spring-to-fall risk period

1 Always
2 Frequently
3 Rarely
4 Never
5 Sometimes I apply this measure, but not to protect myself from Lyme disease
6 Does not apply to my situation
9 I prefer not to answer

Q21Q27r26. Put pesticides on my property

1 Always
2 Frequently
3 Rarely
4 Never
5 Sometimes I apply this measure, but not to protect myself from Lyme disease
6 Does not apply to my situation
9 I prefer not to answer

Q21Q27r27. Mow the lawn regularly on my property

1 Always
2 Frequently
3 Rarely
4 Never
5 Sometimes I apply this measure, but not to protect myself from Lyme disease
6 Does not apply to my situation
9 I prefer not to answer

Q28. With regard to the outside environment of your personal home, what is the statement that best applies to your situation

1 I do not have access to an outdoor yard
2 I have access to an outdoor yard but I do not have the responsibility for its maintenance
3 I have access to an outdoor yard and I have the responsibility for its maintenance 9
I prefer not to answer

Q29. How often did you visit woodlands or areas with tall grass and/or shrubs between May and October this year:

1 More than 25 times
2 From 11 to 25 times

3 From 2 to 10 times
4 Less than 2 times
5 Never
9 I prefer not to answer

Q29a. Thinking of the wooded areas or areas with tall grass and/or shrubs that you visited between May and October, please select the location you visited most frequently by clicking on the map below. You may click on the map until the pin appears in the correct location. When you are satisfied with the location of the pin, click 'Continue'. You will be able to select up to two additional locations in the following questions.

Latitude/Longitude; GCS decimal degrees

Q29a2NA. If you visited other wooded areas or areas with tall grass and/or shrubs between May and October, please select the location you visited by clicking on the map below. If you did not visit additional areas click on "No others". – NO OTHERS

0 Unchecked
1 Checked

Q29a2. If you visited other wooded areas or areas with tall grass and/or shrubs between May and October, please select the location you visited by clicking on the map below. If you did not visit additional areas click on "No others".

Latitude/Longitude; GCS decimal degrees

Q29a3NA. Any others? – NO OTHERS

0 Unchecked
1 Checked

Q29a3. Any others?

Latitude/Longitude; GCS decimal degrees

Q29b. Still thinking of the wooded areas or areas with tall grass and/or shrubs that you visited between May and October, how far from your home did you typically travel?

1 < 1 kilometre
2 1 to 5 kilometres
3 6 to 10 kilometres
4 11 to 20 kilometres
5 21+ kilometres
9 I prefer not to answer

Q29c. Still thinking of the wooded areas or areas with tall grass and/or shrubs that you visited between May and October, how long do you typically spend during these activities?

1	< 1 hour
2	1 to 3 hours
3	4 to 8 hours
4	9 to 24 hours
5	> 1 day
9	I prefer not to answer

Q29d. When you visited the wooded areas or areas with tall grass and/or shrubs between May and October, how often did you walk on cleared paths and trails, avoiding tall grass and plants?

1	Always
2	Frequently
3	Rarely
4	Sometimes, but not because of Lyme disease
5	Never
6	Not applicable
9	I prefer not to answer

Q29e. What were the primary reasons for your visits to wooded areas or areas with tall grass and/or shrubs between May and October?

Q29er1. For work

0	Unchecked
1	Checked

Q29er2. For fitness or recreational activities (hiking/running/biking, etc.)

0	Unchecked
1	Checked

Q29er3. For birdwatching

0	Unchecked
1	Checked

Q29er4. For dog walking

0	Unchecked
1	Checked

Q29er5. For camping

0	Unchecked
1	Checked

Q29er6. For hunting

0	Unchecked
1	Checked

Q29er7. For going to a cottage

0 Unchecked
1 Checked

Q29er96. Other

0 Unchecked
1 Checked

Q29er99. I prefer not to answer

0 Unchecked
1 Checked

Q29er96oe. What were the primary reasons for your visits to wooded areas or areas with tall grass and/or shrubs between May and October – Other

Open response question

Q30. Do you have a dog currently?

1 Yes
2 No
3 I prefer not to answer

Q31. Have you ever had Lyme disease?

1 Yes
2 No 8 Don't know
9 I prefer not to answer

Q31a. Were you diagnosed with Lyme disease by a family physician, general practitioner or medical specialist (e.g. infectious disease specialist, neurologist, cardiologist)?

1 Yes
2 No
3 I prefer not to answer

Q31b. Were you diagnosed with Lyme disease by a naturopath or by other means (e.g. private laboratory testing)?

1 Yes
2 No
3 I prefer not to answer

Q32. Do you personally know anyone who has ever had Lyme disease?

1 Yes
2 No
3 I prefer not to answer

Q33. To your knowledge, have you ever been bitten by a tick?

1	Yes
2	No
3	I prefer not to answer