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CLIMATE CHANGE AND INFECTIOUS DISEASES:

THE CHALLENGES

GUEST EDITOR: DR. NICHOLAS OGDEN

NEXT ISSUE MAY 2, 2019: **THE SOLUTIONS**

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The *Canada Communicable Disease Report* (CCDR) is a bilingual, peer-reviewed, open-access, online scientific journal published by the Public Health Agency of Canada (PHAC). It provides timely, authoritative and practical information on infectious diseases to clinicians, public health professionals, and policy-makers to inform policy, program development and practice.

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The cover photo shows sun rays coming through the trees as a mother and her children go through the forest. Although a lovely scene, they could be at risk for both tick-borne and mosquito-borne diseases. Photo by Shutterstock

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Contact the Editorial Office

phac.ccdr-rmtc.aspc@canada.ca
613.301.9930

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CLIMATE CHANGE AND INFECTIOUS DISEASES: THE CHALLENGES

TABLE OF CONTENTS

EDITORIAL

OVERVIEWS

EDITORIAL

Climate change and infectious diseases: What can we expect?

NH Ogden[1,2]*, P Gachon[3]

Abstract

Global climate change, driven by anthropogenic greenhouse gas emissions, is being particularly felt in Canada, with warming generally greater than in the rest of the world. Continued warming will be accompanied by changes in precipitation, which will vary across the country and seasons, and by increasing climate variability and extreme weather events. Climate change will likely drive the emergence of infectious diseases in Canada by northward spread from the United States and introduction from elsewhere in the world via air and sea transport. Diseases endemic to Canada are also likely to re-emerge.

This special issue describes key infectious disease risks associated with climate change. These include emergence of tick-borne diseases in addition to Lyme disease, the possible introduction of exotic mosquito-borne diseases such as malaria and dengue, more epidemics of Canada-endemic vector-borne diseases such as West Nile virus, and increased incidence of foodborne illnesses. Risk is likely to be compounded by an aging population affected by chronic diseases, which results in greater sensitivity to infectious diseases. Identifying emerging disease risks is essential to assess our vulnerability, and a starting point to identify where public health effort is required to reduce the vulnerability and exposure of the Canadian population.

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Keywords: climate change, vector-borne disease, foodborne, temperature, precipitation, chronic disease, Lyme disease, mosquito-borne diseases

Affiliations

[1] Public Health Risk Sciences Division, National Microbiology Laboratory, Public Health Agency of Canada, St. Hyacinthe, QC

[2] Public Health Risk Sciences Division, National Microbiology Laboratory, Public Health Agency of Canada, Guelph, ON

[3] Étude et la Simulation du Climat à l'Échelle Régionale (ESCER), Université du Québec à Montréal, Montréal, QC

***Correspondence**: nicholas.ogden@canada.ca

Introduction

The articles in this edition of the Canada Communicable Disease Report provide insight into how climate change may increase the number and extent of vector-borne diseases and increase the incidence of foodborne infections in Canada (1–4). In this editorial, we summarize recent and projected future climate change in Canada; how climate change may affect infectious disease emergence and re-emergence; and how, in light of the changing demographics and health of Canadians, these changes may impact risks from infectious diseases.

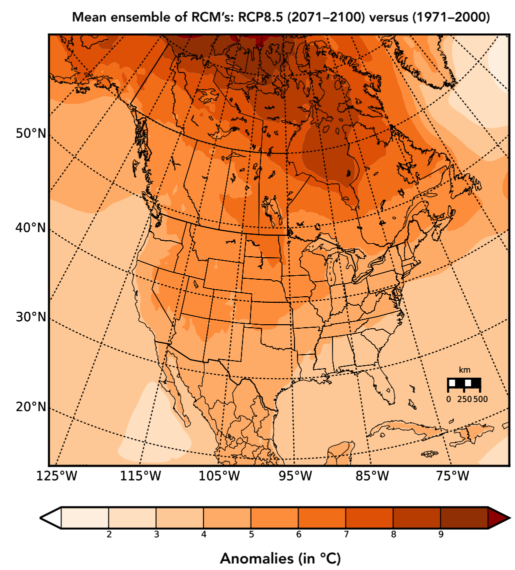
Recent and future climate change in Canada

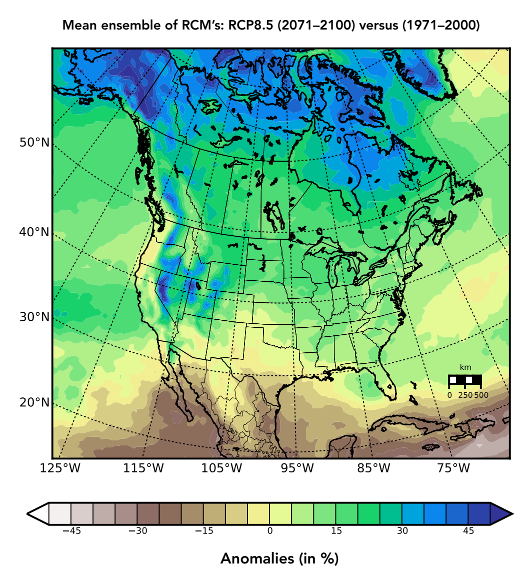
Warming trends have accelerated globally, with overall annual air temperature increases of nearly 1 °C during the period 1880–2017 (5). The years 2015 to 2017 were clearly warmer than any previous years (6), and the last three decades were warmer than any decade since 1850 (7). This trend varies geographically, with greater and faster warming over the Arctic and sub-Arctic basins, particularly in northeastern Canada, due to the rapid decrease of sea-ice and snow cover (8,9).

Since 1948, the rate of warming in Canada as a whole has been more than two times that of the global mean, and the rate of warming in northern Canada (north of 60°N) has been roughly three times or more the global mean (10). Over northeastern Canada (north of 60°N and east of 110°W), the annual mean temperature has increased by 0.75–1.2 °C per decade over the last three decades compared with around 0.18 °C per decade globally (5). Mean air temperature will continue to increase as greenhouse gas concentrations in the atmosphere continue to rise due to human activities.

By the 2070s, most of Canada is projected to be 5 °C warmer than in the period 1971–2000. Predicted changes in annual total precipitation include slight increases in precipitation in the Prairie provinces and greater precipitation (mostly rain) in northern and eastern Canada. However, projections for precipitation are associated with less robust estimates than those for temperature (**Figure 1**).

Figure 1: Projected increases in a) mean annual temperature (in °C) and b) annual total precipitation amount (in %) 2071–2100 compared with 1971–2000

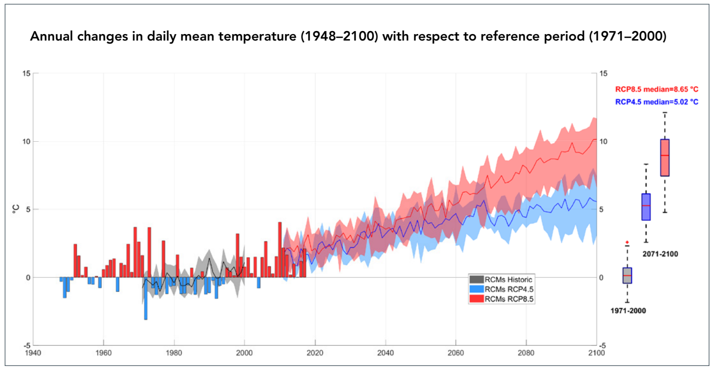




Abbreviations: RCM, regional climate model; RCP, regional concentration pathway
Note: Simulated by nine regional climate models (RCMs) and the available datasets from the North America CORDEX (COordinated Regional climate Downscaling EXperiment) project (11). All simulations use the representative concentration pathway (RCP) 8.5 greenhouse gas emission scenario (12) with a spatial resolution of 0.44 ° around 50 km. Shaded areas correspond to regions where 60% of the models are in agreement in the direction of change and have a magnitude of change higher than the standard deviation of data from the reference period (1971–2000)

In the future, warming is expected to be greater in northeastern Canada (up to 8.65 °C warmer by the 2070s) (**Figure 2**), linked with large declines in sea-ice and snow cover by the end of the 21st century (13).

Figure 2: Observed and projected annual changes in daily mean temperature over northeastern Canada[a]: 1948–2100 compared with 1971–2000



Abbreviations: RCM, regional climate model; RCP, representative concentration pathway
[a] Northeastern Canada is defined as land areas north of 60°N and east of 110°W
Note: Annual changes in daily mean temperature are noted in bar graphs for reference data and line graphs for projected changes. Projected changes were obtained from the same model simulations as used in Figure 1, and using two emissions scenarios of RCP4.5 (blue line) and RCP8.5 (red line), the latter being more realistic at the current time. Shading around the blue and red lines (median of all simulations) illustrates the range of increases in temperatures projected by the different regional climate models. The box-and-whisker plots to the right show the median and ranges of increases in temperatures for the reference period (i.e. observed data), and for the period 2071–2100 (i.e. model projections) under the two different RCPs (12)

Long-term changes in temperature and precipitation are expected to be accompanied by increased variability in temperatures and rainfall from one year to the next, as well as extreme weather events, including heat waves and heavy rainfall events that increases the risks of flooding (13). A significant increase in mean annual precipitation intensity per wet day (up to 15% by the 2070s), but fewer wet days per year, is anticipated in northeastern Canada where warming will be more pronounced over the course of the 21st century. Precipitation intensity is projected to increase substantially over time corresponding with the rate of warming, also affecting southern and eastern areas of Canada.

How climate change may affect infectious disease emergence and re-emergence

Over the past 10 years, we have seen the emergence and re-emergence of infectious diseases globally, including Ebola virus disease in Africa, Middle East respiratory syndrome coronavirus (MERS-CoV) in the Middle East and Zika virus disease, chikungunya, yellow fever and dengue in the Americas. These have posed great challenges for public health.

Infectious diseases emerge due to changes in their geographic ranges and by "adaptive emergence," a genetic change in the microorganisms infecting animals (usually wildlife) that results in these microorganisms becoming capable of infecting humans, and perhaps being transmitted from human to human (14) – in other words a genetic adaptation that leads to a new zoonotic disease.

There are multiple drivers of disease emergence, including those associated with environmental (including climatic) changes; social and demographic changes including globalization; and changes in public health systems and policies (15). Endemic diseases can re-emerge (i.e. increase in incidence or resurge as epidemics) associated with the same drivers. Climate and climate change may directly impact infectious disease emergence and re-emergence via effects on pathogen survival, arthropod vector survival and reproduction, contamination of water and, in the case of zoonoses, abundance of reservoir hosts (the animals that harbour the microbes). Such direct effects of climate change on the ecology, and transmission to humans, of infectious agents have been the focus of previous national (16,17) and international assessments (18–20). However, climate change may have indirect impacts on disease emergence and re-emergence, by affecting other environmental and social changes, and by impacting public health systems.

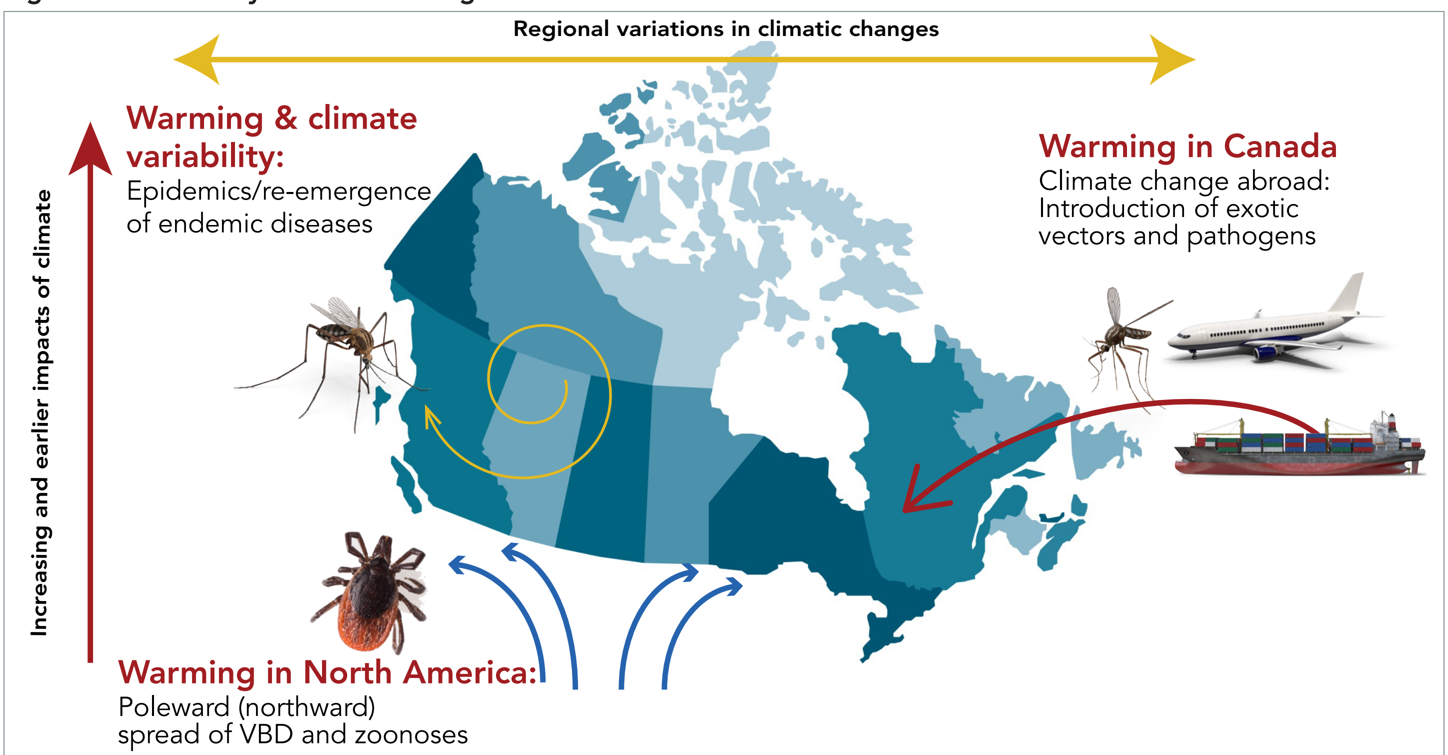
Effects of climate change on ecosystems, including effects on biodiversity, may alter the risk of a new zoonoses originating from wildlife (21,22). In addition, climate change may negatively impact economies globally, particularly those of low and middle income countries. This may directly, or via increased frequency of conflicts, reduce infectious disease control and contribute to increasing densities of infectious agents in countries outside North America. Negative impacts on low- and middle-income economies may drive increased economic or refugee migration, increasing importation of infectious diseases into Canada (23).

The combined effects of all these factors lead to three expected, broad impacts of climate change:

- Increased risks of introduction, and endemic transmission, of "exotic" infectious diseases (both directly transmitted and vector-borne) from around the world (e.g. Severe Acute Respiratory Syndrome [SARS])
- South-to-north spread of diseases currently endemic to the United States (e.g. Anaplasmosis)
- Re-emergence (i.e. more epidemic behaviour and range change) of Canada-endemic infectious diseases (e.g. West Nile virus outbreaks) (**Figure 3**).

The long-term changes in temperature and precipitation, increased climate variability and increased frequency of extreme weather events described above will affect the different infectious disease risks idiosyncratically (24). Modelling studies are increasingly being developed to assist with the prediction of effects of climate change on infectious diseases to allow us to be better prepared for these changing risks.

Figure 3: A summary of climate change effects on infectious disease risks for Canada[a]



[a] Modified (23)

Other factors to consider

Changing patterns of infectious diseases in Canada due to climate change also need to be considered in the context of other disease trends associated with the changing demography and health of Canadians.

The Canadian population is aging and increasingly affected by chronic illnesses. This means that both infectious and chronic disease risks will need to be considered together (25). The risk from infectious diseases comprises two aspects: the likelihood of exposure and sensitivity (i.e. severity of infection outcome). Exposure likelihood depends on the number of infective organisms (the "hazard"), that is, infective humans, microorganisms, arthropod vectors and animal reservoir hosts, in our environment and the rate of contact of humans with infectious organisms. These will likely increase with climate change. At the same time, the severity of infectious disease outcomes will likely be greater in populations that are increasingly elderly and affected by chronic diseases. This seems to be the case for vector-borne viruses such as West Nile virus (26).

Conclusion

Canada's climate is changing. With increased temperatures and spatial and temporal variability in precipitation patterns, this will likely increase the risk of acquiring Lyme disease and West Nile virus, already well-established in Canada, as well as other tick-borne, mosquito-borne and foodborne diseases. More detailed overviews of current and projected from climate change–mediated infectious disease risks are presented in the articles in this issue. Risk is likely to be compounded by the fact that in Canada we have an aging population increasingly affected by chronic diseases who may develop more severe infections than the young and healthy. Identifying these risks is a key activity to assessing our vulnerability as a nation, and a starting point to identifying where public health effort is required to reduce the vulnerability and exposure of the Canadian population.

Authors' statement

NHO and PG conceptualized and co-wrote the article, NHO provided the public health and infectious diseases components and PG provided the information on climate change.

Nicholas Ogden was the Guest Editor of this issue of CCDR, but recused himself from taking any editorial decisions on this manuscript. Decisions were taken by the Editor-in-Chief, Dr. Patricia Huston.

Conflict of interest

None.

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Increased risk of tick-borne diseases with climate and environmental changes

C Bouchard[1,2]*, A Dibernardo[3], J Koffi[2,4], H Wood[3], PA Leighton[2], LR Lindsay[3]

Affiliations

[1] Public Health Risk Sciences Division, National Microbiology Laboratory, Public Health Agency of Canada, St. Hyacinthe, QC

[2] Groupe de recherche en épidémiologie des zoonoses et santé publique (GREZOSP), Faculté de médecine vétérinaire (FMV), Université de Montréal, St. Hyacinthe, QC

[3] Zoonotic Diseases and Special Pathogens, National Microbiology Laboratory, Public Health Agency of Canada, Winnipeg, MB

[4] Center for Food-borne, Environmental and Zoonotic Infectious Diseases, Public Health Agency of Canada, Ottawa, ON

***Correspondence**: catherine.bouchard@canada.ca

Abstract

Climate warming and other environmental changes have contributed to the expansion of the range of several tick species into higher latitudes in North America. As temperatures increase in Canada, the environment becomes more suitable for ticks and the season suitable for tick activity lengthens, so tick-borne diseases are likely to become more common in Canada. In addition to Lyme disease, four other tick-borne diseases (TBDs) have started to emerge and are likely to increase: Anaplasmosis; Babesiosis; Powassan virus; and *Borrelia miyamotoi* disease. Increased temperature increases the survival and activity period of ticks, increases the range of both reservoir and tick hosts (e.g. mice and deer) and increases the duration of the season when people may be exposed to ticks. Other ticks and TBDs may spread into Canada as the climate changes. The public health strategies to mitigate the impact of all TBDs include surveillance to detect current and emerging TBDs, and public health actions to prevent infections by modifying environmental and social-behavioral risk factors through increasing public awareness. Clinical care strategies include patient education, early detection, laboratory testing, and treatment.

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Keywords: climate change, tick-borne disease, Anaplasmosis, Babesiosis, *Anaplasma phagocytophilum*, *Babesia microti*, Powassan virus, *Borrelia miyamotoi*

Introduction

Ticks transmit a wide diversity of bacterial, viral and protozoan pathogens in many tropical and temperate regions of the world (1). Of particular concern in North America are the blacklegged ticks that transmit *Borrelia burgdorferi,* the bacterium that causes Lyme disease (LD) in southern parts of central and eastern Canada (2). It is now widely acknowledged that the increase in temperature associated with climate change has contributed to a general increase in the number, types, level of activity and geographical distribution of ticks in North America (1–11) and has directly contributed to the northward spread of blacklegged ticks and LD into Canada (12). As a result, LD has emerged in Canada and the number of reported cases of Lyme disease continues to rise (13,14).

The purpose of this overview is to summarize the climate and other environmental changes affecting the risk of ticks and tick-borne diseases (TBDs), identify the ticks and TBDs that are occurring or that may spread into Canada and describe the public health and clinical strategies for the management of ticks and TBDs.

The effect of climate and other environmental changes

Climate and other environmental changes are expected to increase the risk of ticks and TBDs in a number of ways. The prevalence, activity and range of a variety of ticks and the pathogens they carry are expected to increase. This is due to changing weather that also causes an increase in the range of animal reproductive and reservoir hosts. Humans are also expected to change their behaviours as the climate changes; bringing both animal hosts and humans into annual contact with ticks over a longer season (15,16). Tick and host habitats can also be affected by factors other than climate.

Increase in number, activity and range of ticks

In Canada, there has been a documented increase in temperature, changes in rainfall patterns and extreme weather events (extreme heat and rainfall) associated with climate change (17). The key climate change effect that has influenced ticks and tick-borne pathogens in Canada, however, is increasing temperature (5). Rising temperature has led to improved conditions for survival and reproduction of ticks and faster development leading to an acceleration of the tick lifecycle (5) that has:

- Increased tick abundance, where tick populations already occur (8)
- Enabled tick populations to spread to higher latitudes (18–23)
- Increased tick activity and questing behavior resulting in longer seasonal activity (5,24)

Prolonged extremes values of temperature (high or low), low humidity and intense rainfall could adversely affect tick development by reducing their activity and increasing their mortality rate (5). These changes in temperature are expected to have less of an effect on ticks than on mosquitoes because of the tick's ability to find refuge in their woodland habitats (5).

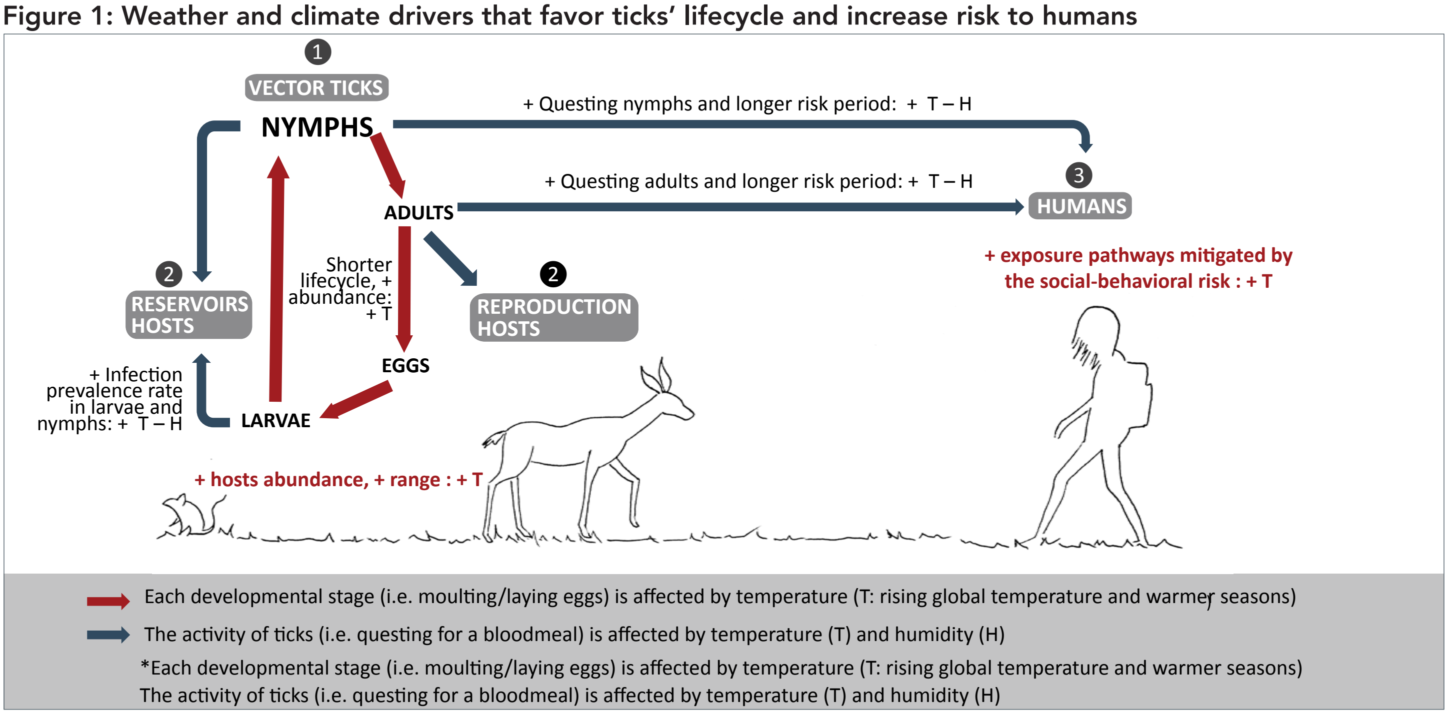
Increase in number, activity and range of hosts

Animals that are reservoir and reproduction hosts are crucial for the transmission cycle of tick-borne pathogens and the tick lifecycle, respectively. The reservoir host is the source of the pathogen for the immature stages of the ticks (25). For most TBDs, the main reservoir hosts are wild rodents, including mice. The reproduction hosts are the source of blood-meals essential for adult female ticks to reproduce. In contrast, the most common reproduction host are deer (26,27). Climate change affects both the reproduction hosts and the reservoir hosts involved in the tick lifecycle and spread of TBDs, respectively (**Figure 1**). Increasing temperatures will expand the distribution range of both rodents and deer (28,29) as well as their abundance and activity (3,29).

Increase in human exposure to ticks

Most ticks are active from the time that the snow melts in the spring until the reappearance of the snow cover in the fall. Typically, questing for a host begins when ambient air temperatures are 4–10°C. As a result of climate change, people may resume outdoor activity earlier in the spring and maintain it longer in the fall. With the increase in length of exposure to tick habitat, combined with an extended season of tick activity, there is an increased likelihood of tick exposure. In contrast, during consecutive hot and dry summer days (heat waves), both outdoor (human) activity and tick activity would likely be reduced. Overall, the risk of climate change on human exposure is more closely related to shorter winters, rather than extreme heat summer weather events.

Figure 1: Weather and climate drivers that favor ticks' lifecycle and increase risk to humans



Adapted from Ogden & Lindsey, 2016 (5)

The main risk groups for TBDs are those:

- Who are engaged in recreational or occupational outdoor activities (e.g. hunting, fishing, hiking, camping, gardening, mushroom or berries picking, dog walking, forestry and farming) in or near endemic areas
- Whose primary or secondary residence is located in or near endemic areas
- Who are either very young (5–9 years of age) or older (55 years of age and older) (30)

Impact of other environmental changes

All tick species have preferred/optimal biomes and environmental conditions that, in part, determine their geographic distribution and consequently the areas of risk for humans (31). Microhabitat features, such as soil characteristics, are critical for tick survival and the successful establishment of new tick populations (32–34). Modifications in habitat characteristics, in parallel with climate change, such as habitat fragmentation, loss of biodiversity, resource availability and land use, affect the dynamics of ticks, their animal hosts and the exposure of ticks to humans (29,35). As an historical example, LD emerged in the United States (US) in the 1970s as a consequence of the reforestation of farmland and the consequent increase in the deer populations, which allowed the expansion of the *Ixodes scapularis* tick populations that were carrying *B. burgdorferi* (3).

Increased tick-borne diseases in Canada

Lyme disease is the most common and well-known tick-borne disease in Canada. At least four other (non-LD) TBDs are emerging in Canada and these are anticipated to increase due to the effects of climate change: Anaplasmosis; Babesiosis; Powassan virus; and *Borrelia miyamotoi* disease.

Lyme disease

Lyme disease is caused by *B. burgdorferi*, which can infect *I. scapularis* ticks in central and eastern Canada and *I. pacificus* ticks in British Columbia. It has been reported in every province from British Columbia to Prince Edward Island (PEI) and it is well-known that LD is on the rise (13). Lyme disease typically presents with an erythema migrans rash and non-specific symptoms such as fatigue, fever, headache and muscle and joint pains and, if left untreated, can become a multisystem disease. Lyme disease is rarely fatal but deaths linked to Lyme carditis have recently been reported (36).

Anaplasmosis

Anaplasmosis is caused by the bacterium *Anaplasma phagocytophilum*, which is spread by *I. scapularis* in eastern and central Canada (37) and *I. pacificus* in British Columbia, and human or animal cases have been reported in most provinces where the ticks occur (38). Clinically, people can have asymptomatic *A. phagocytophilum* infections, but most frequently have non-specific symptoms (e.g. fever, headache and muscle aches). The case fatality rate is less than 1% (39).

Babesiosis

Babesiosis is caused by a malaria-like protozoan *Babesia microti*, which causes a Lyme-like disease. To date, human cases have been reported only in Manitoba (9) but the pathogen has been detected in *I. scapularis* ticks in Manitoba, Ontario, Quebec and New Brunswick (40). The case fatality rate in the US is 2%–5% (39).

Powassan virus

Powassan virus was first detected in Powassan, Ontario and can be found in a number of different tick species. Presentation of Powassan infection can vary greatly, from asymptomatic infections to fatal encephalitis cases (case fatality rate of 10%) (41). Although many of the tick-associated pathogens require an extended period of tick feeding prior to transmission, Powassan virus can be transmitted within 15–30 minutes of tick attachment (42). Two lineages have been identified in vector ticks: Lineage I identified in *Ixodes* in Ontario, Quebec, New Brunswick and PEI; and Lineage II identified in *I. scapularis* from Manitoba, Ontario and Nova Scotia (7).

Borrelia miyamotoi disease

Borrelia miyamotoi was first identified in 2013 in Canada and this pathogen has been found in *I. scapularis* and *I. pacificus* ticks (10). *Borrelia miyamotoi* disease is similar to LD signs but without a rash. Rarely, it can cause meningoencephalitis.

Rarer tick-borne diseases that may emerge

Dermacentor spp. ticks are common and can transmit the bacterium *Rickettsia rickettsii*, which causes Rocky Mountain spotted fever. Typically, fever, severe headache, myalgia, nausea and rash can occur 5 to 10 days after the infection. The estimated case fatality rate is around 5%–10% (39,43). Other spotted fever group rickettsial species may also be transmitted by *Dermacentor* ticks in Canada.

Colorado tick fever virus is currently found in some of the Western US states, and there have been a few reported cases in Saskatchewan and Alberta. It is spread by a tick common in western Canada: *Dermacentor andersoni* (or Rocky Mountain wood tick). Other *Borrelia* species have been found in the upper western and Midwestern states that have spread to a few cases in British Columbia and Ontario. Some *Ehrlichia* species have been found in the Southeastern and South Central US but there have been no human cases detected in Canada.

Table 1 summarizes the human pathogens associated with various tick species in Canada and those in the US that may spread north into Canada with climate change, identifies when a pathogens was first identified as a cause of TBD, its principal reservoir host species, current or historical geographic distribution and whether it has been detected in ticks, humans or other animals.

Table 1: Tick-borne pathogens that are present in or may spread to Canada

Pathogen	Year of ID	Principal tick vector(s)	Principal reservoir host species	Geographic distribution[a]		Nationally notifiable	Detection in Canada		
				Canada	US		Tick	Human	Animal
Anaplasma phagocytophilum	1994	*Ixodes scapularis, Ixodes pacificus*	Rodents	BC, AB, SK, **MB**, **ON**, **QC**, **NB**, NL, **NS**, PEI	Upper MW and NE states	No	Yes	Yes	Yes
Babesia microti	1970	*Ixodes scapularis*	Mice	**MB**, **ON**, QC, **NB**, NS	NE and upper MW states	No	Yes	Yes	Yes
Borrelia burgdorferi	1982	*Ixodes scapularis, Ixodes pacificus*	Rodents	**BC**, AB, SK, **MB**, **ON**, **QC**, **NB**, **NS**, NL, PEI	NE and upper MW states	Yes	Yes	Yes	Yes
Borrelia hermsii	1935	*Ornithodoros hermsi*	Rodents and rabbits	**BC**	Western states	No	---	Yes	---
Borrelia mayonii/ Borrelia mayonii-like	2014	*Ixodes scapularis/ Ixodes angustus*	Rodents	ON, BC	Upper MW states: Minnesota and Wisconsin	No	Yes	---	Yes
Borrelia miyamotoi	2013	*Ixodes scapularis, Ixodes pacificus*	Mice	BC, AB, MB, ON, QC, NB, NS, NL, PEI	Upper MW, NE, and the Mid-Atlantic states	No	Yes	No	---
Colorado tick fever virus	1946	*Dermacentor andersoni*	Golden mantled squirrels, deer mice and rabbits	SK, AB	Western states: Colorado, Utah, Montana, Wyoming	No	No	Yes	---
Ehrlichia chaffeensis	1987	*Amblyomma americanum*	White-tailed deer	---	Southeastern and South Central states	No	No	No	---
Ehrlichia ewingii	1999	*Amblyomma americanum*	White-tailed deer	---	Southeastern and South Central states	No	---	---	---
Ehrlichia muris-like agent	2011	*Ixodes scapularis/ Ixodes muris*	Mice	MB	Upper MW states	No	Yes	---	---
Francisella tularensis	1924	*Dermacentor variabilis, Dermacentor andersoni, Amblyomma americanum*	Rabbits, hares, and rodents	**Canada wide**	All states	Yes	Yes	Yes	Yes
Heartland virus	2012	*Amblyomma americanum*	White-tailed deer	---	MW and South states	No	No	---	---
Lineage I Powassan virus	1963	*Ixodes cookei, Ixodes marxi, Ixodes spinipalpis*	Small and medium-sized woodland mammals (woodchucks)	**ON**, **QC**, **NB**, PEI	NE states and Great Lakes region	No	Yes	Yes	Yes
Lineage II Powassan virus	2001	*Ixodes scapularis, Dermacentor andersoni*	Mice	**MB**, ON, NS	NE and upper MW states	No	Yes	---	---
Rickettsia rickettsii	1909	*Dermacentor variabilis, Dermacentor andersoni, Rhipicephalus sanguineus*	Variety of wild mammals including rodents	**BC**, **AB**, **SK**, **ON**, NS	Eastern, Central, Western and Southwestern states	No	Yes[b]	Yes[b]	Yes

Abbreviations: AB, Alberta; BC, British Columbia; MB, Manitoba; MW, Midwestern; NB, New Brunswick; NE, Northeastern; NL, Newfoundland and Labrador; NS, Nova Scotia; ON, Ontario; PEI, Prince Edward Island; QC, Quebec; SK, Saskatchewan; US, United States; ID, Identification;
Adapted from Paddock et al. 2016 (44)
[a] Canada: Provinces where endemic transmission is known to occur are in bold. For provinces that are not in bold, local pathogen transmission cycles have not been clearly defined and/or infections were detected in adventitious ticks, and/or in humans or animals. US: States where highest incidence rate of human cases were found
[b] Based on historical surveys in ticks in Canada and not recent surveys; human cases of Rocky Mountain spotted fever are also historical; recent cases of spotted fever group *Rickettsia* have been documented but are rare
(-) indicates no data available and/or no studies have been performed

Public health and clinical strategies

A key public health activity to address TBDs is surveillance. Detection of ticks, reporting of human cases and maintenance of accurate information on the overall risk of human exposure to ticks and their associated tick-borne pathogens are necessary to inform clinical care and public health action (45). Currently, active and passive tick surveillance programs in Canada are focused mainly on *I. scapularis*, the main vector of LD. Surveillance efforts are centered on areas where LD did not previously exist or areas where it may not be recognized. As other TBDs emerge, the need for broader surveillance will follow.

Once the risk areas are identified geographically, education and awareness of risk and prevention strategies targeted to people who are at high risk of exposure is central to effective disease prevention. Due to the recent changing range of ticks, and hence the pathogens that they carry, this is especially important in newly-identified at-risk populations because knowledge and perception of risk are currently low (46–48).

Health care providers play an important role in prevention education by informing their patients about the ways to reduce their exposure to vector ticks when travelling, both within Canada and abroad. Risk prevention strategies include applying personal protective measures and making tick checks routine after exposure in high risk areas. Clinicians are also critical for the early detection, obtaining laboratory confirmation and management of these illnesses. Public health efforts include surveillance, environmental modifications and management strategies for ticks and host animals.

Building capacity and awareness is important. For most TBD, early diagnosis and treatment are the most effective ways to reduce serious clinical outcomes. It is suspected that not all cases are currently being detected, reported and/or confirmed. TBDs have substantial clinical overlap (such as fever, headaches, myalgia, and arthralgia). In anticipation of an increase in the types of TBDs in Canada, clinicians need to be aware that if a patient presents with LD-like symptoms and has a negative test for LD, he/she could still have a TBD and further laboratory testing may be indicated. The absence of a rash should not rule out a TBD.

Discussion

In Canada, an ongoing process of emergence and spread of ticks and TBDs is anticipated in localities where climate, weather and habitat favor ticks and transmission cycles of tick-borne pathogens. It is important to note, however, that the relationship between tick-borne diseases and climate is not linear. There are modifiable risk factors that will affect the incidence of TBDs in Canada. These modifiable risk factors include both environmental and human factors. Environmental modification is not minor: one study indicated that removal of leaf litter (detritus and dead leaves) led to a 72%–100% reduction in ticks (49). Knowledge and risk perception about LD have been associated with the degree of adoption of personal tick bite preventive behaviors in Canada (47,48); however, other factors need to be considered. Human population growth, movement and behavior, economics and politics have also been associated with differential rates of human exposure to ticks and the risk of transmission of TBDs (15,16,46). Rapid changes in socio-economic factors concurrent with the climate and other environmental changes underscore the importance of viewing the rising incidence and spread of TBDs as a complex socio-ecological problem, not driven just by climate or other environmental changes, and the need to quantify their relative contributions to the overall burden of disease.

The key climate change drivers and the social-behavioral factors that interact and determine the health outcomes from TBDs are noted in **Figure 2**. One of the challenges going forward will be to appreciate that the rising incidence and geographical spread of TBDs is a complex socio-ecological problem. This also provides opportunities for new intervention strategies. A few studies have addressed the human social-behavioral risk factors associated with TBDs in the context of adaptation to climate change (46–48,50). More sociological studies are needed. Psycho-behavioral studies are also needed to assess how the knowledge that climate change will increase ticks and associated TBDs may be a motivating factor. Finally, it will be important to look for resilience factors or the adaptive capacity of the individuals or communities at risk to minimize the risk of TBDs.

Figure 2: Key climate changes, ecological factors and social-behavioral risks that affect the acquisition of tick-borne diseases

KEY CLIMATE CHANGE DRIVERS AFFECTINGS TICK-BORNE DISEASES

- Temperature
- Precipitation (i.e. intensity and frequency)
- Seasonal weather

ECOLOGICAL RISK

CHANGING PATTERN OF :

VECTOR TICKS
- Abundance (i.e. population size, pathogen infection rate)
- Activity (i.e. questing behaviors or changing seasonal peak/duration)
- Geographic distribution (i.e. range)

RESERVOIR/REPRODUCTION HOSTS
- Abundance (i.e. population size)
- Activity (e.g. daily movement)
- Geographic distribution (i.e. range)

HABITAT
- Landscape change

SOCIAL-BEHAVIORAL RISK

HUMANS
- Outdoor activity
  - Type and duration of activities at risk
  - Shifting months at risk (e.g. early warm spring)
- Social determinants of health
  - Knowledge, preventive behavior (e.g. personal protection) and risk perception toward TBDs
  - Socio-economic risk factors
- Landscape design (e.g. proximity to « woodlands or green areas »)

HEALTH OUTCOMES

Tick-borne diseases after exposure to ticks (i.e. higher likelihood of transmission)

Adapted from Beard et al. 2016 (50)

Conclusion

The expanding geographic range of tick vector species, and the diseases they carry, creates a moving target for clinicians and public health authorities. The clear link with climate change is an opportunity to increase the motivation to address current and emerging TBDs in Canada. While work on addressing climate change will continue more broadly, there is an opportunity to work on other modifiable risk factors that affect TBDs in Canada, appreciating that this is a complex socio-ecological challenge.

Authors' statement

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CB — Conceptualization, writing: original draft, review and editing
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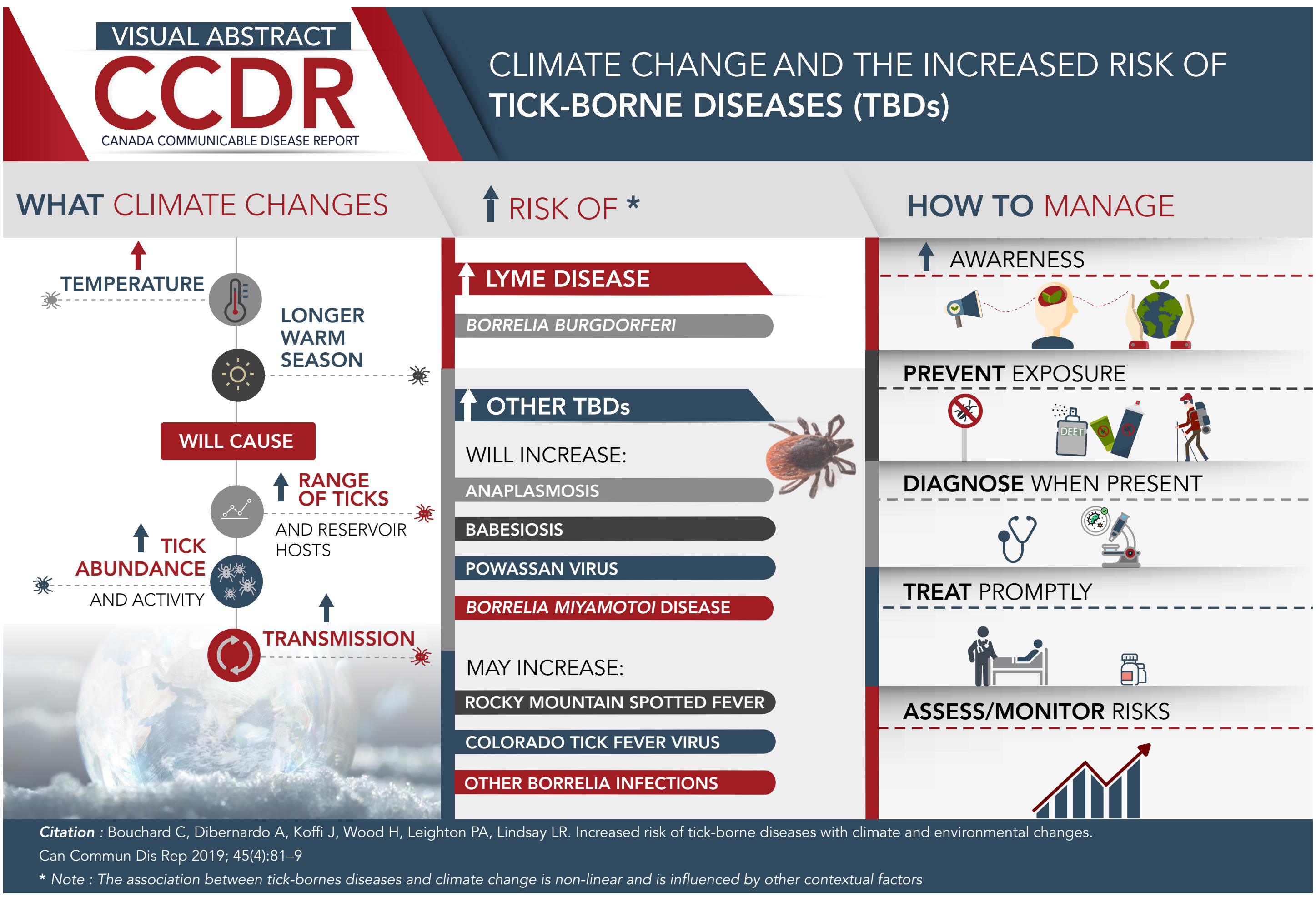

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Increased risk of endemic mosquito-borne diseases in Canada due to climate change

A Ludwig[1]*, H Zheng[2], L Vrbova[3], MA Drebot[4], M Iranpour[4], LR Lindsay[4]

Abstract

There are currently over 80 species of mosquito endemic in Canada—although only a few of these carry pathogens that can cause disease in humans. West Nile virus, Eastern equine encephalitis virus and the California serogroup viruses (including the Jamestown Canyon and snowshoe hare viruses) are mosquito-borne viruses that have been found to cause human infections in North America, including in Canada. Over the last 20 years, the incidence of most of these endemic mosquito-borne diseases (MBD) has increased approximately 10% in Canada, due in large part to climate change. It is anticipated that both the mosquito lifecycle and virus transmission patterns will be affected by climate change, resulting in an increase in both the range and local abundance of several important mosquito species. Laboratory studies and mathematical modelling suggest that increased ambient temperatures, changes in precipitation and extreme weather events associated with climate change will likely continue to drive mosquito vector and MBD range expansion, increasing the duration of transmission seasons and leading to MBD-related epidemics. Furthermore, Canada's endemic MBDs have complex transmission cycles, involving multiple reservoir hosts (birds and mammals), multiple pathogens and multiple mosquito species—all of which may be sensitive to climate and other environmental changes, and making forecasting of potential emerging trends difficult. These expected climate-induced changes in mosquitoes and MBDs underline the need for continued (and expanded) surveillance and research to ensure timely and accurate evaluation of the risks to the public health of Canadians.

Affiliations

[1] National Microbiology Laboratory, Public Health Agency of Canada, St. Hyacinthe, QC

[2] Center for Food-borne, Environmental and Zoonotic Infectious Diseases, Public Health Agency of Canada, Ottawa, ON

[3] Center for Food-borne and Environmental & Zoonotic Infectious Diseases, Public Health Agency of Canada, Toronto, ON

[4] National Microbiology Laboratory, Public Health Agency of Canada, Winnipeg, MN

***Correspondence**: antoinette.ludwig@canada.ca

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Keywords: mosquito-borne disease, West Nile virus, Eastern equine encephalitis, California serogroup virus, endemic, Canada, climate change

Introduction

The United Nations' Intergovernmental Panel on Climate Change report identified mosquito-borne diseases (MBDs) as the infectious diseases that are most sensitive to climate change (1). Canada has already experienced climate changes, and the observed trends have included warming, increased occurrence of extreme heat and heavy rainfall events, and decreased number of frost days (2). These changes are expected to intensify in the coming decades until greenhouse gas emissions start to decrease globally.

These climate changes are expected to influence Canada's flora and fauna in anticipated and unanticipated ways. Included in the fauna that are expected to be affected by climate change are the diverse and plentiful mosquito populations. In addition to being seen as a nuisance due to their bites, a few species can also transmit infectious disease organisms.

This paper focuses on the mosquitoes that are endemic to Canada, and the diseases that they can carry, which are referred to as endemic mosquito-borne diseases. These are distinct from the foreign MBDs that can be acquired outside Canada, although these may emerge in Canada in the future (3). The most medically-important endemic MBD in Canada is West Nile virus (WNV) infection. Other endemic MBDs include Eastern equine encephalitis virus (EEEV) and two California serogroup viruses (CSGV): Jamestown Canyon virus and snowshoe hare virus (4–8). All of these endemic MBDs are transmitted by endemic arboviruses (an acronym for ARthropod-BOrne virus, referring to any virus transmitted by an arthropod vector). Arthropods include mosquitoes, ticks and blackflies; the focus of this paper is specifically on mosquitoes. Arthropod vectors are cold-blooded, so they are especially sensitive to climatic factors.

The objective of this study is to provide an overview of mosquitoes in Canada, summarize how climate change may increase the risk of endemic MBDs, discuss what endemic MBDs are likely to increase both in urban and rural settings and identify what can be done to address these risks.

Endemic mosquito species in Canada

All four of the important endemic to Canada arboviruses (WNV, EEEV, Jamestown Canyon virus and snowshoe hare virus) are transmitted through bites of infected female mosquitoes that have acquired pathogens from specific mammalian or avian reservoir hosts (9). The main mosquito vectors for WNV are *Culex pipiens* and *Cx. restuans* in eastern Canada and *Cx. tarsalis* in western Canada (10). The main vector for EEEV is *Culiseta melanura* (11,12) and the main vectors for CSGV are a variety of non-Culex mosquitoes species (e.g. *Aedes*, *Culiseta* and *Anopheles* species) (13–15). Included in the CSGV are Jamestown Canyon and snowshoe hare viruses. The reservoirs for these pathogens vary between the mosquito species; for example, the main animal reservoir of Jamestown Canyon virus is the white-tailed deer (16), while for snowshoe hare virus it is (not surprisingly) the snowshoe hare and other small mammals (8). Humans are incidental or "dead-end" hosts for the endemic arboviruses; meaning that although they can be infected, they cannot subsequently transmit viruses to feeding mosquitoes with any efficiency due to low and transient viremia (4,10). Arboviruses can also occasionally be transmitted by blood transfusion or tissue transplants (17,18).

In addition to these traditionally endemic mosquitoes, many additional species have been introduced into Canada over the past few decades. In the 1970s, a comprehensive review of the insects and arachnids of Canada reported that there were 74 mosquito species (19). In the intervening 40 years, six species have been reported as newly established in Canada: *Ochlerotatus ventrovittis*; *Oc. japonicus*; *Cx. salinarius*; *Cx. erraticus*; *An. perplexens*; and *An. crucians* [(20), and *M Iranpour unpublished data*]. In addition, the geographic range of 10 species has expanded in Canada: *Uranotaenia sapphirina*; *Cs. melanura*; *Cs. minnesotae*; *Cx. tarsalis*; *Oc. sticticus*; *Oc. spencerii; Oc. dorsalis; Oc. nigromaculis; Oc. campestris;* and *Oc. cataphylla* (21). So there are now approximately 80 mosquito species in Canada.

Recently, invasive *Aedes* species have been found in southern Ontario and southern Quebec. Small numbers of *Aedes albopictus* were detected in parts of Windsor-Essex County in southern Ontario in 2016, 2017 and 2018 (22). The repeated detection of this species, over a number of collections sites, suggests that this species is now becoming endemic in this part of Canada. Specimens of *Ae. aegypti* were also collected at some of the same sites in Windsor, Ontario in 2016 and 2017 and at a single site in southern Quebec in 2017. Although these two *Aedes* strains are well known for transmission of exotic (non-native to Canada) MBD (3), they can also be a vector for MBDs already endemic to Canada, including WNV.

Climate change will increase the risk of endemic mosquito-borne diseases

The key aspects of climate change that affect endemic mosquitoes are increases in temperature, and changes in rainfall patterns. An increase in precipitation generally increases the potential egg-laying and larval habitat for mosquitoes in the environment. The relationship is often non-linear, with above average rainfall generally increasing the abundance of mosquitoes by increasing the availability of standing water, while excessive or violent precipitation can play a leaching role and destroy the eggs and flush larvae from selected habitats (23). Elevated temperatures can increase rates of development of immature stages of the mosquito lifecycle, leading to higher reproductive rates and exponential population increases (24,25). These elevated temperatures shorten the extrinsic incubation period, so mosquitoes that have acquired infection become infectious sooner; for example, outbreaks of WNV infection appear to occur more frequently in Canada when seasonal temperatures are above average, as these conditions promote rapid build-up of virus in vector mosquitoes and favour extended host-seeking by potentially infected female mosquitoes (26). It has been reported that in Korea and Japan, the duration of the transmission season can be extended by several months when average summer temperatures increase by as little as 5°C (27). Changes in rainfall affect the availability of standing water, which is where mosquitoes lay their eggs and where immature mosquitoes live. Consequently, changes in rainfall strongly affect mosquito reproduction (28,29).

The impact of climate change on WNV transmission in Canada has been investigated in two studies with similar conclusions (30,31). Chen and colleagues (30) examined WNV transmission in the Prairies (where *Cx. tarsalis* is the main vector) and have projected an extension of seasonal activity of WNV-infected *Cx. tarsalis* from three months (June to August) to five months (May to September) by the 2080s. These authors also predicted a northward range expansion for *Cx. tarsalis* and WNV. Hongoh et al. (31) modelled the potential distribution of *Cx. pipiens* populations in eastern Canada and predicted a similar northward range expansion for this eastern vector of WNV.

Birds and some mammals are important reservoirs for WNV and other MBDs. For WNV, a wide range of bird species serve as reservoirs, including corvids (i.e. crows, jays and magpies) and passerines (i.e. robins, sparrows, finches and starlings) (10,32–34). For other MBDs, mammals, such as deer, squirrels, chipmunks and hares, are the reservoir hosts. Climate change could affect these reservoir host populations in several ways, influencing their abundance and species distributions. It is possible that climate change could also affect individual and population health of the reservoir hosts as the more abundant viruses could also harm them directly.

It is important to note that proliferation of mosquitoes and MBDs can also be affected by other environmental changes, including land-use changes, as well as vector control activities (35,36). Habitat loss and fragmentation (37) can also impact avian and mammal reservoirs (38).

Current and emerging endemic mosquito-borne diseases

Different mosquito species have different characteristics with respect to preferred habitats and pathogen load. With climate change, WNV may increase in both urban and rural areas whereas other MBDs, such as EEEV and CSGV, may increase, particularly in rural areas. The following provides a short description of the current and emerging endemic MBDs.

West Nile virus may increase in both rural and urban areas

West Nile virus is transmitted by *Cx. pipiens*, which is largely an urban mosquito, and *Cx. tarsalis*, which is largely a rural mosquito. Effects of climate change may affect WNV risk, particularly in urban areas in the east, and rural areas in the Prairies. The increase of number of mosquitoes, including those infected with MBDs, will have a more significant impact on public health in urban areas because that is where the vast majority of Canadian resides. Early symptoms of WNV include fever, headache, skin rash, nausea and muscle aches. Most affected people recover fully, but approximately 1% develops severe illness (meningitis, encephalitis, acute flaccid paralysis and poliomyelitis). Those over 70 years of age with underlying medical conditions and those who are immunocompromised are at greater risk of severe illness (39–42).

Since 2002, the annual reported incidence of WNV human cases has fluctuated significantly, ranging from 1,481 in 2003 to five cases in 2010 and 2,215 cases in 2007, which may be due in part to variations in weather affecting mosquito reproduction and virus transmission and variation in reporting (43). Geographical variation in the number of reported human cases of WNV has been dramatic as well: in 2003 and 2007 most human cases of WNV were reported from the Prairie regions (Alberta, Saskatchewan and Manitoba), but in 2002, 2012 and 2018 most cases occurred in Ontario and Quebec (43). This geographic variation is likely associated with local effects of weather on the different vectors, and on virus transmission and again, to some variation in reporting (28,29,44).

Eastern equine encephalitis and California serogroup viruses will increase in rural areas

Eastern equine encephalitis virus is transmitted by *C. melanura* mosquitoes, which thrive in freshwater swamps (11,12). The reservoir for this virus is avian hosts. Eastern equine encephalitis infection can be asymptomatic, or present as one of two types of illness: systemic or encephalitic. Approximately a third of all people with encephalitis will die from the disease (45). A single human EEEV case was reported in Ontario in 2016 (43). Eastern equine encephalitis has been responsible for sporadic outbreaks in horses (and exotic birds) in Ontario since 1939 (46). Atypically large outbreaks of EEEV in horses were reported in Ontario, Quebec and Nova Scotia in 2008, 2009 and 2010 (46).

California serogroup viruses are transmitted via a number of mosquito species. The CSGV can cause febrile illness and neurologic disease (47). New testing methods were introduced in 2005 and over 200 probable and confirmed cases of CSGV were reported to the Public Health Agency of Canada and/or provincial public health laboratories from 2005 to 2014 (*M Drebot unpublished data*). Cases have been identified in all provinces as well as in the Northwest Territories and other northern regions. As well, seroprevalence studies have identified rates of exposure as high as 20%–40% or greater in specific regions of Canada [(*48–50), and M Drebot unpublished data*]. Since 2015, between 20 and 40 human cases have been observed annually in Canada, with the exception of 2017, when 122 cases were reported (43). This dramatic increase may be due, at least in part, to enhanced testing of those who presented with a WNV-like illness (patients were negative when tested for WNV, so further testing was requested). Based on the National WNV and other Arbovirus Report, there were more than 100 cases of Jamestown Canyon and snowshoe hare viruses in Quebec in 2017 (*H Zheng, H Wood and M Drebot, National WNV and other Arbovirus Report, unpublished report*). It is quite likely that CSGV cases are under-diagnosed due to the low level awareness of these pathogens among physicians and other health care practitioners.

Current clinical and public health response

In the absence of vaccines or specific treatments, reducing mosquito habitat, reducing mosquito bites, early and accurate testing for MBDs in humans and ongoing surveillance form the core of the clinical and public health response.

Preventive measures: preventing mosquito bites prevents infection

There is no vaccine or specific treatment for WNV, EEEV or CSGV infections, so prevention of infective mosquito bites is the cornerstone of control (43). Bites can be reduce by covering the skin (e.g. wearing long pants and loose-fitting shirts with long sleeves) and/or by using insect repellent containing the chemicals *N*,*N*-diethyl-3-methylbenzamide (DEET) or icaridin (51). Reducing mosquito habitat near homes, mainly by removing standing water, is also important. Municipalities, often in collaboration with provincial governments, have also funded mosquito abatement programs designed to reduce the size of nuisance and vector mosquito populations. The scope of these programs is highly variable across Canada but typically involve source reduction (removal of standing water), application of larvicides to standing water and, less frequently, aerial or vegetative treatments with products designed to kill adult mosquitoes.

Early diagnosis and testing of arboviruses

Early detection of MBDs is important to avoid potentially severe complications. Diagnosis of arbovirus infections can be challenging as patients often initially present with non-specific symptoms. The diagnosis of MBDs must be confirmed with laboratory testing. The National Microbiology Laboratory (Winnipeg) is the reference lab for EEEV and CSGV testing and for WNV for the provinces with low WNV occurrences (i.e. Newfoundland and Labrador, Prince Edward Island, Nova Scotia and New Brunswick). The provinces with higher WNV occurrences do their own testing.

Surveillance

The World Health Organization has highlighted the importance of identifying and monitoring various vector populations as a component of global surveillance, including mosquitoes that may carry and transmit arboviruses, as surveillance for risk in mosquito populations is more timely than waiting for human disease cases to appear (52).

Currently, surveillance for arboviruses varies somewhat across jurisdictions in Canada and much of the effort has focused in the Prairies, Ontario and Quebec, where disease incidence is typically highest. For WNV, mosquito surveillance involves the counting of the different species of mosquitoes and calculating the infectivity rate in species that carry WNV. This surveillance approach needs to be expanded in terms of the geographical areas and the MBDs that are monitored. By doing this, changing boundaries of WNV can be tracked and the emergence of mosquitoes infected with EEEV, Jamestown Canyon virus, snowshoe hare virus and more can be detected to inform public health action.

Since WNV is currently a notifiable disease in Canada, surveillance includes monitoring the incidence of human infections, including detection the presence of WNV in blood donations (all donations are tested for a wide range of diseases and pathogens). In addition, mortality and morbidity trends in wild bird populations and in horses and other domesticated animals are monitored. These data are collected by provinces and territories for action by these jurisdictions, but surveillance information is also transferred to, synthesized and analyzed by the Public Health Agency of Canada, to provide a national picture that is disseminated to provincial and territorial partners on a weekly basis (43).

Since EEEV, Jamestown Canyon and snowshoe hare virus infections are not currently nationally notifiable diseases in Canada, there are no national surveillance programs to monitor their activity in mosquitoes, reservoirs or human populations. Nevertheless, the National Microbiology Laboratory tested for these arboviruses in patients who presented with symptoms consistent with arboviral infections; identifying cases of both Jamestown Canyon and snowshoe hare virus infections (8,43). The National Microbiology Laboratory has also carried out seroprevalence studies for other orthobunyaviruses, such as Cache Valley virus. Cache Valley virus can cause neurological disease in both humans and livestock (53) and cases of symptomatic illness have been associated with positive serology in patients from Manitoba, Saskatchewan and Alberta (*M Drebot unpublished data*).

Discussion

Climate change will undoubtedly influence the extent to which viruses are spread by endemic mosquitoes in the future, with increases in numbers and populations of endemic species (including those associated with arboviruses) and with introduction of new species (and associated pathogens) into Canada. Predicting how MBDs will respond to changes in climate is challenging: mosquitoes, reservoirs and the environment differ in their dependencies on climate change (54,55). This means that even modest climate changes may drive large increases in arbovirus transmission (1,56).

In addition, each MBD has unique transmission cycles, reservoirs and vectors. These may exist only in selected regions of Canada, so changes in prevalence of MBDs will be different from one region/landscape/habitat to another. It is anticipated that WNV will increase in both the rural and urban areas and the other currently endemic arboviruses (i.e. EEEV and CSGV) will increase in the rural areas.

There is a need to further explore the possible impacts of climate change on WNV, EEEV and CSGV in Canada. Ideally, these studies should consider and model each transmission cycle as a whole, not focusing only on one aspect, such as mosquito density or reservoir population dynamics. It will be important to advance our surveillance capacity not only for the expansion of existing arboviruses into new geographical areas but also for the appearance of new arboviruses, and to conduct research studies to better understand the changing and potentially expanding dynamics of arbovirus transmission dynamics.

The portrait of endemic mosquito species in Canada is always changing, and these changes in mosquito species (type, distribution and activity) are exacerbated by changes in our climate; clinicians and public health professionals will need to be aware of how these changes may impact MBD across Canada. We expect that the mean number of cases will increase, in conjunction with an increase in the number of different types of endemic arboviruses, in a relatively sporadic and unpredictable way. This will require a heightened vigilance from front line public health professionals as well as testing/surveillance laboratories.

Conclusion

Climate change is anticipated to have significant effects on Canada's endemic mosquito populations and thus on MBDs such as WNV, EEEV and CSGV. MBDs have complex transmission cycles, involving multiple reservoir hosts (birds and mammals), and sometimes multiple mosquito species—all of which may all be differentially sensitive to climate and other environmental changes. Since WNV is a reportable disease, some data exists on disease prevalence and how this has changed over time, but much less is known about EEEV and CSGV. Reporting, and adequate treatment, is complicated by the symptoms of the MBDs, which may be less than definitive. The sporadic appearance of some MBDs has hampered the implementation of diagnostic testing for selected arboviruses at the provincial level and centralization of testing (at the National Microbiology Laboratory) is more cost effective for some arboviruses.

The expected climate-induced changes in mosquitoes and MBDs underline the need for continued surveillance and research to ensure timely and accurate evaluation of the public health risks to Canadians. Public health professionals and clinicians need to promote awareness among Canadians of this important public health risk and be vigilant for the emergence and spread of new strains of mosquitoes and new mosquito-borne diseases.

Authors' statement

AL — Principal writer
HZ — Co-writer and reviewed drafts
LV — Co-writer and reviewed drafts
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LRL — Co-writer and reviewed drafts
MI — Co-writer and reviewed drafts

Conflict of interest

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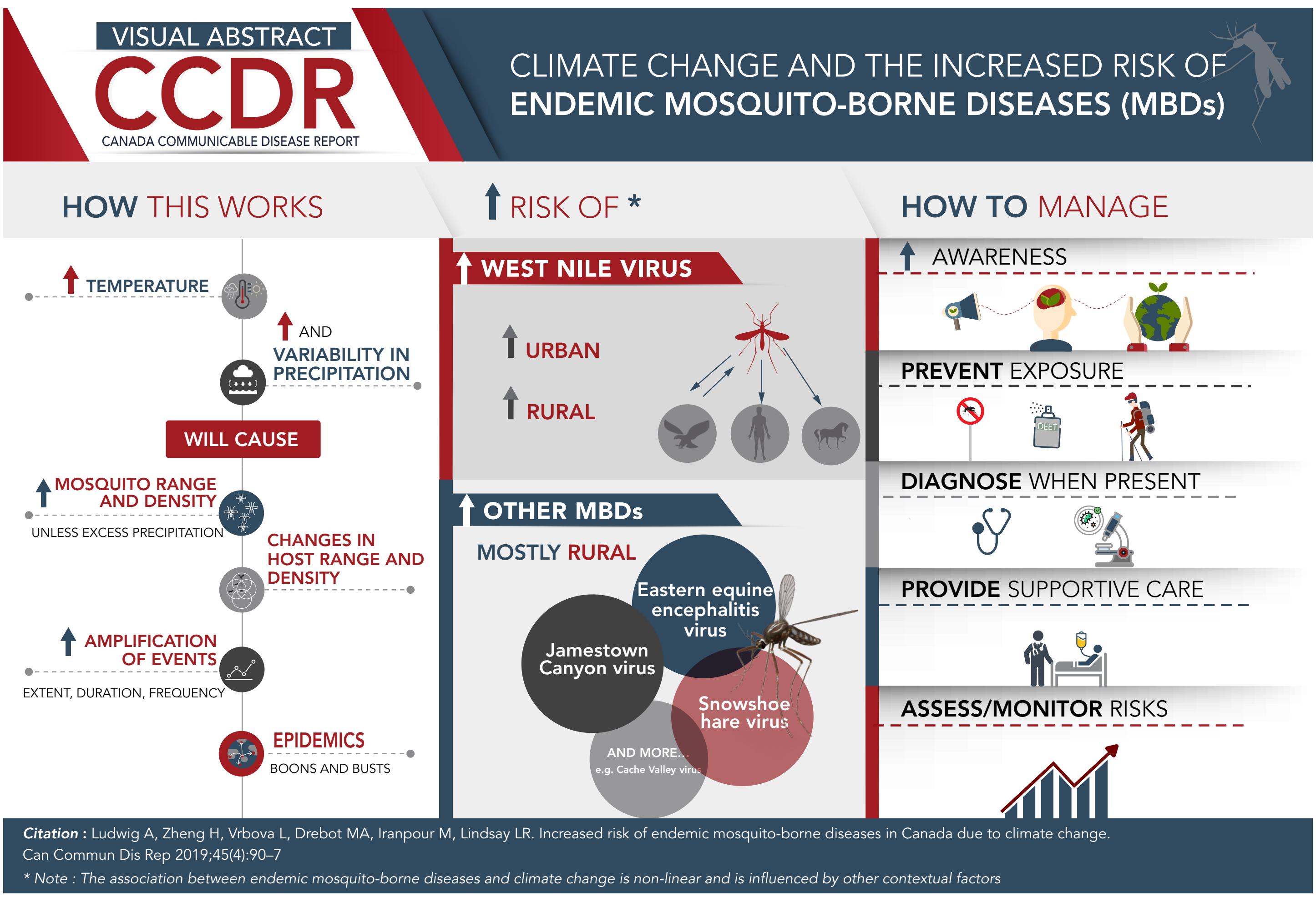

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OVERVIEW

Could exotic mosquito-borne diseases emerge in Canada with climate change?

V Ng[1]*, EE Rees[1], LR Lindsay[1], MA Drebot[1], T Brownstone[1,2], T Sadeghieh[1,3], SU Khan[1,3]

Abstract

Of the 3,500 species of mosquitoes worldwide, only a small portion carry and transmit the mosquito-borne diseases (MBDs) that cause approximately half a million deaths annually worldwide. The most common exotic MBDs, such as malaria and dengue, are not currently established in Canada, in part because of our relatively harsh climate; however, this situation could evolve with climate change. Mosquitoes native to Canada may become infected with new pathogens and move into new regions within Canada. In addition, new mosquito species may move into Canada from other countries, and these exotic species may bring exotic MBDs as well. With high levels of international travel, including to locations with exotic MBDs, there will be more travel-acquired cases of MBDs. With climate change, there is the potential for exotic mosquito populations to become established in Canada. There is already a small area of Canada where exotic *Aedes* mosquitoes have become established although, to date, there is no evidence that these carry any exotic (or already endemic) MBDs. The increased risks of spreading MBDs, or introducing exotic MBDs, will need a careful clinical and public health response. Clinicians will need to maintain a high level of awareness of current trends, to promote mosquito bite prevention strategies, and to know the laboratory tests needed for early detection and when to report laboratory results to public health. Public health efforts will need to focus on ongoing active surveillance, public and professional awareness and mosquito control. Canadians need to be aware of the risks of acquiring exotic MBDs while travelling abroad as well as the risk that they could serve as a potential route of introduction for exotic MBDs into Canada when they return home.

Affiliations

[1] National Microbiology Laboratory, Public Health Agency of Canada, Guelph, ON, St. Hyacinthe, QC and Winnipeg, MB

[2] Dalla Lana School of Public Health, University of Toronto, Toronto, ON

[3] Department of Population Medicine, University of Guelph, Guelph, ON

***Correspondence**: victoria.ng@canada.ca

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Introduction

Mosquitoes cause approximately half a million deaths annually through the transmission of a range of mosquito-borne diseases (MBDs) (1). The majority of MBDs, including malaria, dengue, chikungunya virus (CHIKV) and Zika virus (ZIKV), are transmitted to humans by mosquitoes that are not currently established in Canada (2–4). Most of the important vectors are mosquitoes from the *Aedes* and *Anopheles* genera. These mosquitoes are exotic to Canada because our cooler climate and particularly our harsh winters, prevent these mosquitoes from becoming established here. In contrast, mosquitoes that are endemic to Canada, including *Culex pipiens*, *Cx. restuans* and *Cx. tarsalis*, which are the primary vectors for West Nile virus in Canada, can survive over winter by entering diapause and, in general, have lower developmental temperature thresholds than tropical/subtropical species (5). Accordingly, MBDs transmitted by exotic mosquitoes are restricted to being acquired abroad, while MBDs transmitted by endemic mosquitoes are acquired both abroad and locally in Canada during the warmer months of the year (6–10).

It is well known that MBDs are sensitive to climate, and that climatic conditions set the limits on the geography and seasonality of transmission; this is reflected in the distinct and often predictable seasonal distribution of MBDs (11). A question that is often asked is: might climate change enable exotic MBDs to emerge and become established in Canada? The objectives of this paper are to identify the following: the exotic mosquitoes that carry pathogens causing human diseases; travel-acquired cases of exotic MBDs that have been reported in Canada; the climatic changes that could create local ecosystems in Canada that are conducive to the survival of exotic mosquitoes and the transmission of exotic MBDs; the potential routes of introduction of exotic MBDs into Canada as a result of climate change; and a summary of the clinical and public health implications.

Exotic mosquitoes that carry pathogens that cause human diseases

There are approximately 3,500 known species of mosquitoes worldwide, but only a small number can carry and transmit pathogens that cause illness in humans. The most prolific carriers and transmitters of exotic diseases to humans are *Aedes* genus mosquitoes. These mosquitoes, in particular *Ae. aegypti* and *Ae. albopictus*, have the potential to transmit over 20 pathogens that are infectious to humans including dengue, CHIKV, ZIKV and yellow fever (12,13). *Aedes aegypti* and *Ae. albopictus* are more widely distributed globally than any other mosquito species that are known to transmit diseases to humans (2,3). Collectively, their impact is far-reaching: between 1952 and 2017, the overall numbers of countries/territories reporting autochthonous mosquito-borne transmission of dengue, CHIKV, ZIKV and yellow fever were estimated to be 111, 106, 85 and 43, respectively (14). The highly anthropophilic behaviour of *Ae. aegypti* and *Ae. albopictus* makes them two of the most medically-important mosquito species worldwide (15).

The *Anopheles* genus of mosquitoes also carry and transmit pathogens that cause diseases of importance to humans; these include malaria and lymphatic filariasis (**Table 1**). Up to 41 *Anopheles* species have been identified as vectors for malaria (4); three of these are co-carriers of parasites causing lymphatic

Table 1: Common vectors of exotic mosquito-borne diseases in humans and the main diseases they carry

Mosquito genus	Mosquito species or species complex	Global distribution	Main disease/s carried	References
Aedes	*Ae. aegypti*	North and South America, Middle East, Africa, India/Western Asia and Southeast Asia and the Pacific	CHIKV, dengue, YF and ZIKV	(2,3,14)
	Ae. albopictus[a]	North and South America, Europe and Middle East, Africa, India/Western Asia and Southeast Asia and the Pacific	CHIKV, dengue and ZIKV (to a lesser degree than *Ae. aegypti*)	(2,3,14,20)
	Ae. polynesiensis	South Pacific Islands	LF (*W. bancrofti*) and dengue	(12)
	Ae. scapularis	North and South America	LF (*W. bancrofti*)	(12)
	Ae. pseudoscutellaris	South Pacific Islands	LF (*W. bancrofti*) and dengue	(12,21,22)
Anopheles	*An. albimanus, An. albitarsis, An. aquasalis, An. darlingi, An. freeborni*[b], *An. marajoara, An. nuneztovari, An. pseudopunctipennis, An. quadrimaculatus*[b]	North and South America	Malaria	(4,19)
	An. atroparvus, An. labranchiae, An. messeae, An. sacharovi, An. sergentii, An. superpictus	Europe and Middle East	Malaria	(4)
	An. arabiensis, An. funestus[c], *An. gambiae*[c], *An. melas, An. merus, An. moucheti, An. nili*	Africa	Malaria Malaria and LF (*W. bancrofti*)[c]	(4,12,23)
	An. culicifacies, An. stephensi, An. fluviatilis	India/Western Asia	Malaria	(4)
	An. aconitus, An. annularis, An. balabacensis, An. barbirostris[d], *An. culicifacies, An. dirus, An. farauti, An. flavirostris, An. fluviatilis, An. koliensis, An. lesteri, An. leucosphyrus/latens, An. maculatus, An. minimus, An. punctulatus, An. sinensis, An. stephensi, An. subpictus, An. sundaicus*	Southeast Asia and the Pacific	Malaria Malaria and LF (*B. timori*)[d]	(4,12)
Culex	*Cx. tritaeniorhychus*	Southeast Asia and the Pacific, Africa, Middle East	JE, Rift Valley fever, Murray Valley encephalitis virus	(24,25)
	Cx. quinquefasciatus	North, Central and South America, Southeast Asia	LF (*W. bancrofti*)	(12,23)
Mansonia	Various species	Asia and the Pacific	LF (*B. malayi*)	(12,23)

Abbreviations: *Ae.*, *Aedes*; *An.*, *Anopheles*; *B.*, *Brugia*; CHIKV, chikungunya virus; *Cx.*, *Culex*; JE, Japanese encephalitis; LF, lymphatic filariasis; *W.*, *Wuchereria*; YF, yellow fever; ZIKV, Zika virus
[a] Species that have recently established in Canada (20)
[b] Species that are established in Canada (19)
[c] Species (*An. funestus* and *An. gambiae*) that transmit both malaria and LF (*W. bancrofti*)
[d] Species (*An. barbirostris*) that transmit both malaria and LF (*B. timori*)

filariasis (12). Each vector has a distinct geographic dominance with multi-species coexistence, and distribution is generally worldwide across the tropics and subtropics (4,16). Globally, they are responsible for autochthonous malaria transmission in 87 countries, with a concentration of cases in Africa and India (17). Concomitantly, over 70 countries in sub-Saharan Africa, Southeast Asia and the Pacific Islands report local lymphatic filariasis transmission (18). Of the most common mosquitoes carrying diseases exotic to Canada, only two are established here (Table 1); *An. freeborni* and *An. quadrimaculatus*, the principal vectors for malaria. Additionally, *Ae. albopictus*, a principal vector for dengue, CHIKV, ZIKV and yellow fever, appears to have emerged and established in a very limited part of Southwestern Ontario in 2017 (19,20). Other mosquitoes that carry diseases exotic to Canada include *Culex* and *Mansonia* species. Diseases that are carried by these mosquitoes include lymphatic filariasis, Japanese encephalitis, Rift Valley fever and Murray Valley encephalitis (12).

Travel-acquired exotic mosquito-borne diseases

International travel is very common; approximately 4.75 million Canadian residents returned from abroad each month between 2014 and 2018; 3.77 million (82%) from the United States (US) and 985,000 (21%) from elsewhere (26). The most common destinations outside of the USA are Mexico, Western Europe and the Caribbean (including Cuba, Dominican Republic and The Bahamas) (27). It is, therefore, not surprising that Canadian residents often return with sporadic travel-acquired exotic MBDs; the most common being malaria and dengue (9,28,29). Each year, approximately 500 cases of travel-acquired malaria are reported in returned travellers (30). While dengue is not a notifiable disease in Canada, the National Microbiology Laboratory identified over 250 cases between 2012 and 2017, and a significant number of additional cases were documented by provincial public health laboratories in the same time period (*unpublished data, Michael Drebot, National Microbiology Laboratory, Winnipeg, Canada*). Dengue is currently considered one of the most critical MBDs worldwide and is of concern for Canadian residents given the 30-fold increase in global incidence over the past 50 years (31,32). The recent incursion of CHIKV and ZIKV into the western hemisphere and subsequent epidemic in the Caribbean and the Americas demonstrate the potential for exotic MBDs to spread extensively and rapidly across large vulnerable populations (33,34). As a result of the presence of MBDs worldwide, including in countries frequented by Canadian travellers, hundreds of residents returned to Canada with travel-acquired CHIKV and ZIKV between 2013 and 2017 (7,8,10,35). Other common MBDs of concern for returned travellers include yellow fever, Japanese encephalitis and lymphatic filariasis. The recent outbreaks of yellow fever in Brazil and parts of Africa are a threat for Canadian residents travelling in those regions (36–38), although confirmed cases in returned travellers remain low (14 cases between 2008 and 2016) (30) possibly due to the highly effective yellow fever vaccine recommended for Canadian travellers (39,40). The number of travel-acquired Japanese encephalitis and lymphatic filariasis cases is unknown as these diseases are not notifiable in Canada, but it is expected to be considerable given their high annual incidence globally (1). Collectively, exotic MBDs result in thousands of travel-acquired infections annually in returned travellers.

Climate changes may create ecosystems for exotic mosquitoes

All parts of Canada are expected to experience climate change, but the impact will vary across regions, with the highest impact expected in the north (41). A global warming of approximately 2°C is expected to bring milder temperatures, increased precipitation and humidity and more frequent extreme heat and precipitation events. As a result, winters are expected to be milder and shorter, while summers will be warmer and longer. A global warming of approximately 4°C is very likely to cause even greater changes, with extreme heat events, daily-scale precipitation extremes and a further increase in annual precipitation across most parts of Canada, but particularly in the north (41). There are many ways in which these climate changes are expected to facilitate the emergence and transmission of exotic MBDs in Canada. Warmer temperature, higher humidity and increased precipitation will facilitate the lifecycle of exotic mosquitoes by supporting larval development and survival and extending adult lifespan, thus increasing overall population size (42–45). Climate change is also expected to influence disease transmission via several mechanisms:

- Reducing egg development time in recently-fed adult female mosquitoes, thus reducing the time between blood meals and increasing feeding frequency (42,43,46)
- Shortening the extrinsic incubation period, thereby allowing mosquitoes to become infectious faster (42,43,45–48)
- Increasing mosquito longevity, enabling infectious mosquitoes to bite more people (44)

As temperatures in Canada become milder and humidity and precipitation increase, larger parts of Canada will become climatically suitable for the establishment of some exotic mosquitoes that are currently limited to the tropics and subtropics (3,49,50). Furthermore, as the winters become shorter and summers become longer, the duration of climatic suitability for disease transmission will increase, allowing autochthonous transmission of exotic MBDs for a limited period in some regions of Canada (49). For exotic MBDs that are zoonoses and require an animal reservoir that is currently present in Canada (e.g. Japanese encephalitis), climate change could have further impact on the reservoir such as maintaining and supporting the expansion of natural habitats and prolonging the availability of food sources, thus increasing population size (51,52). Extreme weather events, such as droughts and heat events, can bring host reservoirs searching for water sources and mosquito breeding grounds together (53–55).

Introduction of exotic mosquito-borne disease pathogens into Canada

For exotic MBD emergence, a competent mosquito vector, an appropriate reservoir host (if any) and the exotic pathogen must be brought together in a suitable habitat. While climate change can create additional habitats for mosquitoes and reservoir hosts, the pathogen needs to be introduced into Canada either via infected mosquitoes, viraemic humans and/or viraemic reservoirs (56,57). Pathogen introduction can occur either locally or globally.

Local introduction can occur during short-distance movement of mosquitoes/reservoirs/humans from a neighbouring endemic region into Canada. Exotic MBDs that may emerge through local introduction include Saint Louis encephalitis virus and La Crosse encephalitis virus because their vectors are already present in Canada and endemic in the US (58–60). If climate change influences or leads to increased seasonal abundance and expansion of specific mosquito vectors (e.g. *Ae. triseriatus*), there is a higher risk for the spread of these pathogens to additional geographic regions in the country. Locally-acquired cases of exotic MBDs will likely emerge, with a high possibility of these diseases becoming endemic over time.

Global introduction can arise from long-distance movement (international travel, migration or trade/transportation of goods) of mosquitoes/reservoirs/humans from a distant endemic region into Canada. There are two global introduction scenarios in which vectors are either present or absent in Canada (**Table 2**). When the vector is present, climate change will likely increase travel-acquired cases of exotic MBDs by amplifying the natural transmission cycle and the likelihood of contact between vectors/reservoirs/humans in the country of origin, permit short-lived autochthonous transmission in Canada (as observed for CHIKV and ZIKV elsewhere) (61–66) with the possibility of becoming endemic over time (as demonstrated by West Nile virus) (6,67–69). Diseases that may emerge under this scenario include malaria and CHIKV, because established or recently-emerged vector populations of these diseases are already present in Canada (19,20). When the vector is absent, and restrictions in the ecological niche of vectors may prevent establishment even with climate change, the impact of climate change will be limited to an increase in travel-acquired cases with no further local mosquito-borne transmission. While some types of global movement are linked to climate change [e.g. climate refugees (70) and changes in travel patterns (71)], many are not; however, global movement is increasing (72) and Canadians are avid travellers (26), so even without the influence of climate change, global movement will continue to support emergence of exotic MBDs in Canada.

Clinical and public health implications

As climate change is anticipated to increase the risks for introduction of exotic MBDs into Canada and travel- and locally-acquired exotic MBDs in Canadian residents, vigilant clinical and public health response is essential. Clinicians should maintain a high level of awareness of current exotic MBD trends, promote mosquito bite prevention strategies by travellers, be aware of the laboratory tests needed for early detection and report notifiable diseases to public health. Public health professionals should focus on supporting ongoing active surveillance of exotic mosquitoes and pathogens, promoting public and professional awareness of exotic MBDs and mosquito control, including bite prevention. Canadian travellers need to be more aware of the risks that they could be acquiring exotic MBDs while travelling abroad as well as the risk that they could serve as a potential route of introduction for exotic MBDs into Canada. They can do this by seeking advice from local travel medicine clinics or by reviewing the travel health and safety sections of the government website (travel.gc.ca) prior to leaving the country.

Discussion

The most common travel-acquired exotic MBDs in Canada are malaria, dengue, CHIKV and ZIKV (7–10,28,29). Exotic mosquitoes that carry and transmit these diseases to humans are from the *Anopheles* and *Aedes* genera (12). Currently, most of these mosquitoes are not present in Canada, but *An. freeborni* and *An. quadrimaculatus* (principal vectors for malaria) are widespread. Small numbers of *Ae. aegypti* and *Ae. albopictus* (principal vectors for dengue, CHIKV, ZIKV and yellow fever) have been introduced into parts of Canada and populations of the latter have recently established in a very limited region in Canada (19,20).

Climate change is expected to create and expand suitable habitats for exotic and endemic mosquitoes and their host reservoirs (3,42,50–52,74,75) and allow for establishment of exotic MBDs. Physiological changes in mosquitoes would increase their survival and ability to transmit diseases to humans (42–48). In addition, lengthening the duration of climatic suitability for disease transmission (49,76) could occur simultaneously both in Canada and in countries where exotic MBDs are already circulating. Climate change will also have an impact on the movement of vectors/reservoirs/humans and thus influence the introduction of exotic MBDs into Canada (70,71).

Table 2: Three routes of introduction of exotic mosquito-borne pathogens into Canada

Consideration	Local movement	Global movement, vector/s present	Global movement, vector/s absent
Emergence arising from local or global movement	Short-distance movement at the local scale	Long-distance movement at the global scale	Long-distance movement at the global scale
How geographic emergence may occur in Canada	Natural and regular movements of vectors/reservoirs/humans from a neighbouring endemic region	International travel, trade/transportation and migration of vectors/reservoirs/humans from a distant endemic region	International travel, trade/transportation and migration of vectors/reservoirs/humans from a distant endemic region
Pathogen	Present in a neighbouring endemic region (i.e. bordering a US state) but not in Canada	Present in a distant endemic region but not in Canada	Present in a distant endemic region but not in Canada
Vector mosquitoes present	Yes	Yes	No
Impact of climate change on emergence	Amplify the natural transmission cycle and increase the likelihood of contact between vectors/reservoirs/humans in Canada	Amplify the natural transmission cycle and increase the likelihood of contact between vectors/reservoirs/humans in Canada and in the country of origin Pathogen must be imported into Canada via infected mosquitoes or viraemic humans/reservoirs (driven primarily by global movement and partially by climate change)	Amplify the natural transmission cycle and increase the likelihood of contact between vectors/reservoirs/humans in Canada and in the country of origin Pathogen must be imported into Canada via infected mosquitoes or viraemic humans/reservoirs (driven primarily by global movement and partially by climate change)
Current disease presentation in Canada	Travel-acquired cases from the US	Travel-acquired cases from the US and globally	Travel-acquired cases from the US and globally
Diseases that may emerge in Canada with climate change	SLEV and LCEV virus via established *Cx. tarsalis/pipiens/restuans* (SLEV) and *Ae. triseriatus* (LCEV) populations [73]	CHIKV via the emergence of *Ae. albopictus* in Canada (20) or malaria via established *An. freeborni* and *An. quadrimaculatus* populations (19)	JE, Rift Valley fever and other exotic MBDs where a natural competent vector is not present in Canada (Table 1)
Anticipated disease emergence in Canada with climate change	Locally-acquired cases High possibility of becoming endemic over time	Increase in travel-acquired cases Autochthonous cases or short-lived autochthonous outbreaks transmitted by emerging or established vector populations Possibility of becoming endemic over time	Increase in travel-acquired cases, but no further local mosquito-borne transmission

Abbreviations: *Ae.*, *Aedes*; *An.*, *Anopheles*; CHIKV, chikungunya virus; *Cx.*, Culex; JE, Japanese encephalitis; LCEV, La Crosse encephalitis virus; MBD, mosquito-borne disease; SLEV, Saint Louis encephalitis virus; US, United States

The relationship between climate and MBDs is not linear. For example, temperatures above a certain threshold may reduce mosquito survival or slow pathogen replication in mosquitoes (77,78). Thus, climate change can have an opposing effect on disease transmission such as supporting reservoir hosts while reducing pathogen and mosquito survival. There are other factors that will have a profound impact on exotic MBD emergence, including demographic changes (immigration and population growth) (79–82), increased mobility and interconnectivity (79–81,83), urbanization and land use (79,80,82), and socioeconomic factors (79–82,84,85); and some of these factors will also be influenced by climate change.

While the short-term risk of exotic MBD incursion and establishment in Canada, facilitated or exacerbated by climate change, is very low (49), it is feasible. The establishment of a new MBD has already been seen historically with West Nile virus (6,67,69,86,87). Malaria is of particular concern given that it was once endemic in Canada (88), a suspected autochthonous case was reported in 1996 (89) and two dominant vectors are widespread in Canada (19). Exotic MBDs transmitted by *Ae. albopictus* are also of concern, with the recent incursion of this species into temperate regions elsewhere that are climatically similar to parts of Canada (61,64,65,90) and the emergence of one small region in Canada where *Ae. albopictus* appears to have become established (20). Range expansion of this species within Canada will need to be monitored closely.

Conclusion

The exact impact of climate change on exotic MBD emergence in Canada is difficult to quantify but there are expected to be more travel-acquired cases, a higher potential for short-lived autochthonous outbreaks of exotic MBDs and a higher risk for exotic MBDs to become endemic, particularly if the vectors are already present in Canada. Overall, there is a risk of establishment of exotic mosquitoes and MBDs in Canada with climate change, especially those transmitted by *Aedes albopictus* mosquitoes. Some of these impacts can be mitigated by adopting clinical and public health measures, including promoting awareness and use of mosquito bite prevention strategies, early detection and prompt response, ongoing active surveillance and mosquito control. Canadians need to be aware of the exotic MBDs that they are at risk for while travelling abroad as disease risk will only increase with climate change. Further, Canadians returning home serve as a potential route of introduction for exotic MBDs, making the need for awareness even more urgent.

Authors' statement

VN — Conceptualization, investigation, writing of original draft, supervision and project administration
EER — Writing: review and editing
LRL — Writing: review and editing
MAD — Writing: review and editing
TB — Investigation, writing: review and editing
TS — Investigation, writing: review and editing
SUK — Investigation, writing: review and editing

Conflict of interest

None.

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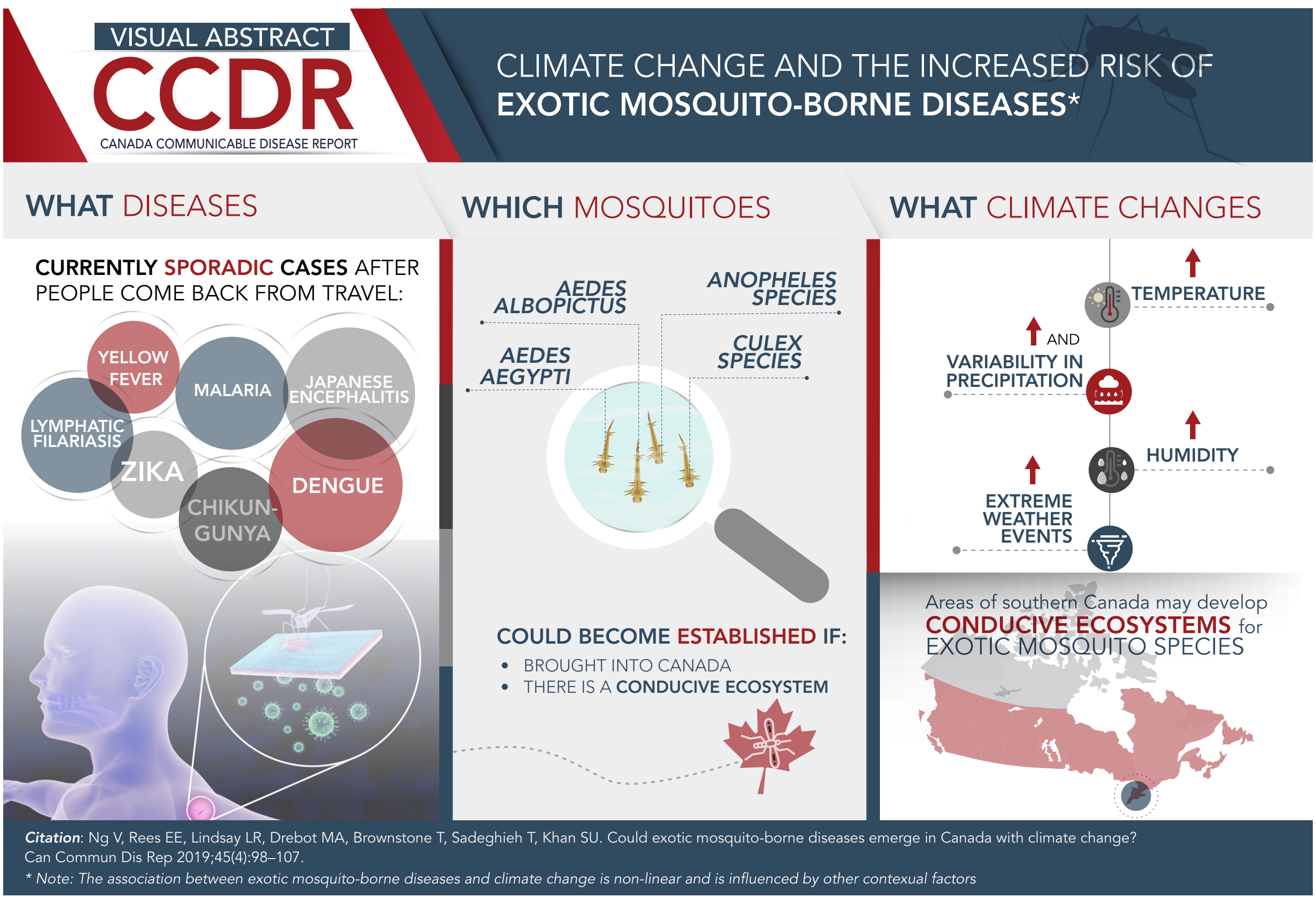

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OVERVIEW

How will climate change impact microbial foodborne disease in Canada?

BA Smith[1]*, A Fazil[1]

Abstract

Foodborne disease is a major concern in Canada and represents a significant climate change-related threat to public health. Climate variables, including temperature and precipitation patterns, extreme weather events and ocean warming and acidification, are known to exert significant, complicated and interrelated effects along the entire length of the food chain. Foodborne diseases are caused by a range of bacteria, fungi, parasites and viruses, and the prevalence of these diseases is modified by climate change through alterations in the abundance, growth, range and survival of many pathogens, as well as through alterations in human behaviours and in transmission factors such as wildlife vectors. As climate change continues and/or intensifies, it will increase the risk of an adverse on food safety in Canada ranging from increased public health burden to the emergence of risks not currently seen in our food chain. Clinical and public health practitioners need to be aware of the existing and emerging risks to respond accordingly.

Affiliation

[1] National Microbiology Laboratory, Public Health Agency of Canada, Guelph, ON

***Correspondence**: ben.smith@canada.ca

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Keywords: food safety, foodborne disease, Canada, climate change

Introduction

Many of the recently observed climate changes have been unprecedented over the preceding decades to millennia (1,2). The projected changes to climate variables in Canada, including temperature and precipitation metrics, are well-documented (3). In particular, annual average air and water temperatures and precipitation are expected to rise across the country, with regional and seasonal variations (4). Already the consequences of climate change within Canada are evident (2), and additional wide ranging and significant effects on many areas are expected, including on the prevalence of foodborne diseases. The World Health Organization recently released a report estimating the burden of foodborne illnesses caused by 31 hazards (bacteria, viruses, parasites, toxins and chemicals), where they estimated that, worldwide, these hazards caused 600 million foodborne illness and 420,000 deaths in 2010 (5). In Canada alone, there were an estimated four million cases of microbial foodborne diseases per year in the time period from 2000 to 2010 (6). Hence, an increase in cases of foodborne disease due to climate change would exacerbate an already important public health concern in Canada.

Food safety, food security and food system challenges are thought to represent the most significant climate change-related threats to human health globally (7–12). Researchers anticipated a link between foodborne illness and climate change, since the pathogens that cause many foodborne infectious diseases are known to be influenced by climate and weather variables (13–21). Despite their obvious importance, these food safety issues have received little attention in the climate-health literature relative to other health indicators (12). The purpose of this paper is to provide a summary of how climate change will increase the risk of microbial foodborne diseases, and what can be done to address this.

Effect of climate change on foodborne illness

The climate variables that most influence foodborne illness are increased air temperature, water temperature and precipitation (13,14). These variables affect foodborne illness through three mechanisms: abundance, growth, range and survival of pathogens in crops, livestock and the environment (22); human exposure factors, including cooking practices, food handling and food preferences that are influenced by a longer period of warm temperatures; and transmission factors, such as wildlife vectors, that transfer pathogens to food.

Studies from regions with similar climate and seasonality to Canada have linked foodborne contamination and disease incidence with seasonal trends (13,14). These studies reported a strong association between increasing air and water temperatures and an altered and extended summer season for non-cholera *Vibrio* species (spp.) infections. So strong was this sensitivity to climate that it was proposed that non-cholera *Vibrio* spp. can act as a barometer of climate change in marine systems (23). Similarly, a time-series analysis showed that rates of enteric illness varied seasonally within Canada, with a strong association between infections with *Campylobacter* spp., pathogenic *Escherichia coli* and *Salmonella* spp., and ambient air temperature (24). These results are generally similar to those reported from other countries (13–17,25,26).

The growth, survival, abundance and range of pathogens will be affected by climate change throughout the food chain. Growth and survival of pathogens is intrinsically linked to climate factors (often ambient temperature) (14); for example, survival of *E. coli* is dependent on temperature, moisture and interactions with the microbial community (27), with greater growth at higher temperatures, within limits (28). Livestock stressed at higher temperatures may shed greater amounts of enteric pathogens (29,30), affecting pathogen prevalence in crops, the environment and produce. Pathogens could expand their range and become established in new regions of Canada as climate conditions become more favourable for their growth. Precipitation events can move pathogens through the environment and contaminate food sources such as crops or livestock facilities.

Human exposure factors are also related to climate change. As the summer season lengthens, a greater number of food mishandling events leading to cross contamination or undercooking are anticipated. Increased food mishandling by consumers is due in part to differences in cooking preparation methods (e.g. barbeque, a commonly used cooking technique in the summer) or different consumption patterns (e.g. picnics) (18,31,32). Contamination of meat products with *Salmonella* spp. in Canada is similar throughout the summer season compared with the rest of the year (*unpublished data, BA Smith, National Microbiology Laboratory, Guelph, Ontario*), yet human cases of salmonellosis increase throughout this time of year in some regions (24,31). This suggests that human exposure factors drive salmonellosis rates (31), which themselves are driven by climate. Food preferences are likely to change due to increased food availability; for example, a lengthened summer growing season can result in more fresh produce consumption, which is also linked to foodborne illness (33,34).

Finally, climate change can impact foodborne illness indirectly, through increased activity, range expansion and reproduction rates of wildlife vectors (35). Wildlife vectors can transmit pathogens to food in a number of ways. The presence of rodents and insects, including beetles, flies and litterbugs, on farms is associated with increased *Campylobacter* spp. contamination in chicken broiler flocks (36). Produce such as lettuce or strawberries are generally grown in rural areas and fields are susceptible to intrusion of wildlife such as deer, which are known carriers of human pathogens (37,38). *Vibrio* ssp. can be transmitted to oysters in marine environments through phytoplankton, zooplankton and copepod vectors (39). The impact of climate change on each of these vectors can result in changes to foodborne contamination and disease.

Current and emerging foodborne illnesses

When the causative agent is identified, the five bacteria that account for over 90% of foodborne illnesses in Canada are norovirus, *Clostridium perfringens*, *Campylobacter* spp., *Salmonella* spp. and *Bacillus cereus* (**Table 1**) (6). Four of these pathogens have been shown to be influenced by climate variables. Given the projected changes to climate in Canada, it is anticipated that the overall burden from these and other pathogens will increase. Additional pathogens ranked lower in Canada (6), for which there is a known link between climate and foodborne diseases, are also included in Table 1. Although generalizations are apparent (e.g. an increase in extreme events, precipitation and temperature increases incidence of many foodborne diseases), the precise impact of climate change is pathogen- and commodity-specific. The incidence of *Vibrio* spp. has been linked to air temperatures, consumption practices and water temperatures (40,41) and it is anticipated that the relative ranking of *Vibrio* spp. will increase with climate change.

Other foodborne disease issues

There are other less common foodborne infections that are likely to increase with climate change and add to the burden to personal and public health. Mycotoxins, produced by fungi growing in crops such as corn and cereal grains, proliferate with increased air temperature, humidity and precipitation (45). Increased temperature stress or alterations to livestock housing conditions as a result of climate change could also drive increased antimicrobial use in food-producing animals, which might increase occurrence of antimicrobial-resistant foodborne illness in humans (46). Because climate change is a global issue, and because Canada imports a significant percentage of its foodstuffs especially in the winter months, impacts on contamination of imported foods with pathogens exotic to Canada are expected.

Clinical and public health response

The medical and public health systems as well as the public will need to prepare for the anticipated amplification in the rate of illness from known foodborne pathogens and the emergence of illness from either exotic or less well-known pathogens. Clinicians need to stay informed on foodborne illness trends to better recognize and diagnose cases and, when indicated, treat them in the light of known trends in antimicrobial resistance. Public health needs to prepare for more outbreaks. Laboratory capacity will need to increase to detect the increase in persistent as well as emerging infections. There will be a need for increased public awareness of this climate-related trend and the importance of good food safety practices. And as always, there will be a need for strengthening our surveillance systems to monitor changing trends to better understand the changing profile of illness and the distribution of animal reservoirs.

Table 1: Key foodborne pathogens currently ranked in Canada to consider in the context climate change (6)

Pathogen	Symptoms (42)	Current cases per 100,000 people (6)	Influence of climate on occurrence (20,43)
Norovirus	Symptoms include nausea, vomiting, diarrhea, stomach cramps, low-grade fever, chills, headache, muscle aches and fatigue	3,223.79	Extreme weather events (such as heavy precipitation and flooding) and decreased air temperature
Clostridium perfringens	Symptoms include diarrhea, pain and cramps, stomach bloating, increased gas, nausea, weight loss, loss of appetite, muscle aches and fatigue. In rare cases, severe dehydration, hospitalization, death	544.50	Uncertain
Campylobacter spp.	Symptoms include fever, nausea, vomiting, stomach pain, and diarrhea. In rare cases, hospitalization and long-lasting health effects, death	447.23	Changes in the timing or length of seasons, increased air temperatures, precipitation and flooding
Salmonella spp., nontyphoidal	Symptoms include chills, fever, nausea, diarrhea, vomiting, stomach cramps, and headache. In rare cases, hospitalization and long-lasting health effects, death	269.26	Changes in the timing or length of seasons, extreme weather events, increased air temperatures
Bacillus cereus	Symptoms include diarrhea or vomiting. In rare cases, hospitalization and long-lasting health effects, death	111.60	Changes in the timing or length of seasons, drought
Verotoxigenic *Escherichia coli* non-O157	Symptoms include diarrhea. In rare cases, hospitalization and long-lasting health effects, death	63.15	Changes in the timing or length of seasons, extreme weather events, increased air temperatures
Verotoxigenic *Escherichia coli* O157	Symptoms include diarrhea. In rare cases, hospitalization and long-lasting health effects, death	39.47	Changes in the timing or length of seasons, extreme weather events, increased air temperatures
Toxoplasma gondii	Symptoms include minimal to mild illness with fever. In rare cases, inflammation of the brain and infection of other organs, birth defects	28.10	Extreme weather events, increased air temperatures, precipitation (44)
Vibrio parahaemolyticus	Symptoms include diarrhea, stomach cramps, nausea, vomiting, fever and headache. In rare cases, liver disease	5.53	Extreme weather events, increased air temperatures, increased sea surface temperature
Listeria monocytogenes	Symptoms include fever, nausea, cramps, diarrhea, vomiting, headache, constipation, muscle aches. In severe cases, stiff neck, confusion, headache, loss of balance, miscarriage, stillbirth, premature delivery, meningitis, death	0.55	Extreme weather events, increased air temperatures, precipitation
Vibrio vulnificus	Symptoms include diarrhea, stomach cramps, nausea, vomiting, fever, headache. In rare cases, liver disease	<0.01	Extreme weather events, increased air temperatures, increased sea surface temperature

Abbreviations: spp., species; <, inferior to
Note: Currently, the five most common foodborne pathogens are norovirus, *Clostridium perfringens, Campylobacter spp., Salmonella spp. and Bacillus cereus*

Discussion

Climate change will increase the risks from existing and emerging foodborne diseases, primarily through increases in extreme events, increases in air and water temperatures, and changes to precipitation frequency and intensity. It is important to note, however, that these trends regarding foodborne illness and climate change involve complex systems with many interacting factors (47).

The impact of climate change on foodborne disease is not a linear relationship, as it involves modifiable risk factors. Efforts to minimize the incidence and impact of climate-related foodborne illness should focus on these modifiable factors through farm-level interventions such as vector control, processor interventions such as improved cleaning procedures and modifying human behaviours to promote food safety. Other factors will also impact the incidence of foodborne illness, including an aging and increasingly diverse population and changes to imported foods; many of these factors are themselves influenced by climate change, yet often not explicitly considered in climate change and food safety research.

Future directions

Cross-disciplinary research using various methodological tools can provide insight and forecast disease transmission patterns under specific climatic conditions (48). One promising example is mathematical modelling, as it can be used to provide better insights into the complexities of climate and infection interactions and allow for testing of various adaption or mitigation measures to counteract the negative impacts of climate change on food safety. Modelling studies apply a set of logical assumptions to predict, with an inevitable degree of uncertainty, how risks may develop in the future. A risk modelling framework specific to Canada has been developed (50). It provides a structured platform for constructive, transparent discussion around the state of knowledge on climate change impacts on food safety. The framework has been used to project the potential climate change impacts on public health for mycotoxins in wheat, protozoa in drinking water, and *Vibrio parahaemolyticus* in oysters to better understand the range of food and water safety related implications of climate change (49).

Conclusion

The prevalence of foodborne illnesses is likely to increase with climate change. This is attributed to anticipated increases in both the pathogens that already commonly cause foodborne illness and the emerging pathogens, including those that produce mycotoxins and other rare pathogens, which have been found to be present in some imported foods. The treatment of foodborne illness will be complicated by trends in antimicrobial resistance; however, the effect of climate change on foodborne illness is not linear due to a number of modifiable risk factors, and this needs to be the focus of both clinical and public health efforts. Additional research, including those using techniques such as mathematical modelling, can identify new approaches to prevention, early detection and mitigation.

Authors' statement

BAS — Conception, analysis and data interpretation, writing and editing
AF — Conception, writing and editing

Conflict of interest

None.

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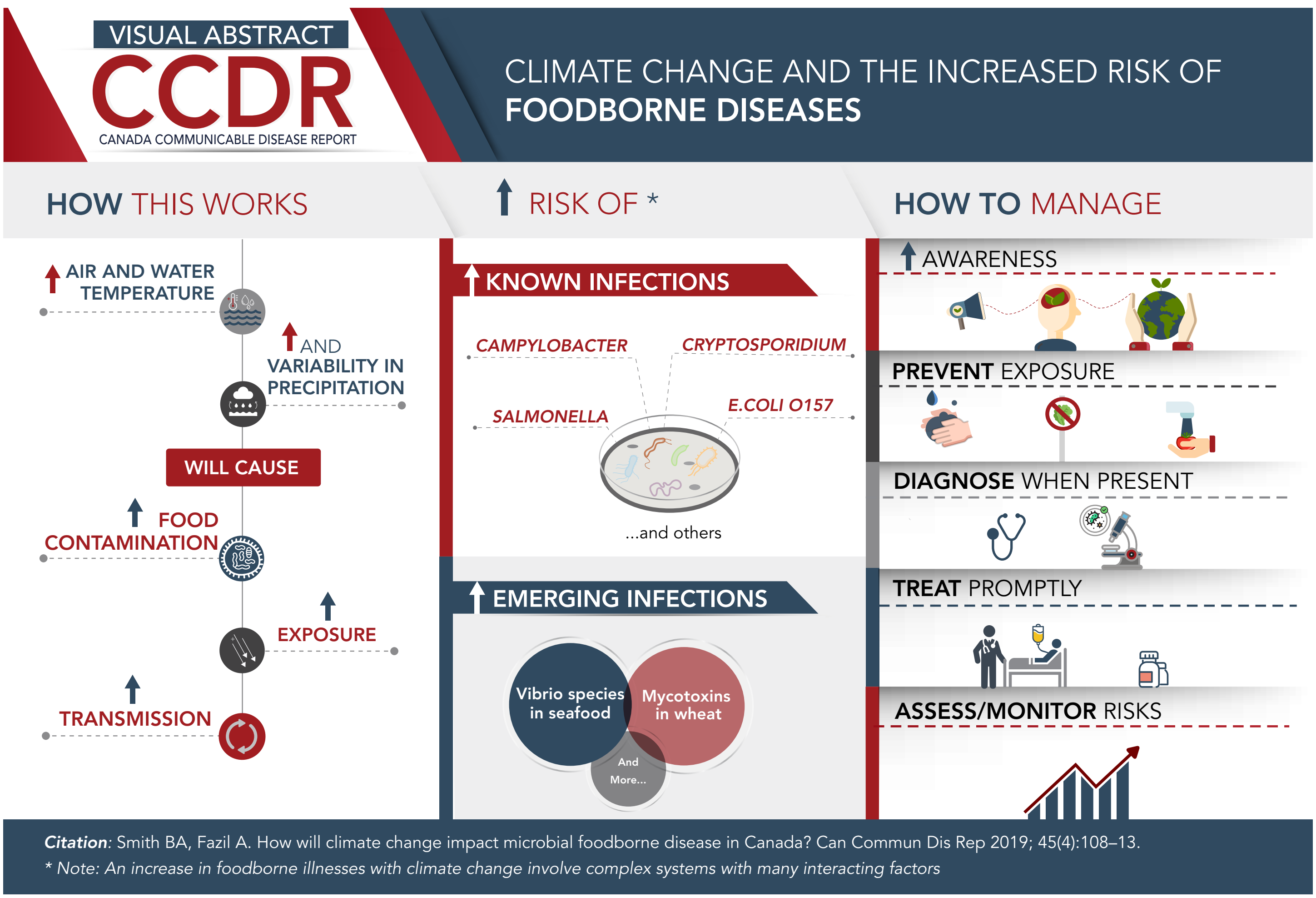

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Public Health Agency of Canada
130 Colonnade Road
Address Locator 6503A
Ottawa, Ontario K1A 0K9
phac.ccdr-rmtc.aspc@canada.ca

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