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

V Ng1*, EE Rees1, LR Lindsay1, MA Drebot1, T Brownstone1,2, T Sadeghieh1,3, SU Khan1,3

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.


Keywords: mosquito-borne disease, Canada, climate change, international travel, exotic vectors, Aedes albopictus, Culex mosquitoes, Anopheles species

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>
<thead>
<tr>
<th>Mosquito genus</th>
<th>Mosquito species or species complex</th>
<th>Global distribution</th>
<th>Main disease/s carried</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Aedes</em></td>
<td><em>Ae. aegypti</em></td>
<td>North and South America, Middle East, Africa, India/Western Asia and Southeast Asia and the Pacific</td>
<td>CHIKV, dengue, YF and ZIKV</td>
<td>(2,3,14)</td>
</tr>
<tr>
<td></td>
<td><em>Ae. albopictus</em>¹</td>
<td>North and South America, Europe and Middle East, Africa, India/Western Asia and Southeast Asia and the Pacific</td>
<td>CHIKV, dengue and ZIKV (to a lesser degree than <em>Ae. aegypti</em>)</td>
<td>(2,3,14,20)</td>
</tr>
<tr>
<td></td>
<td><em>Ae. polynesiensis</em></td>
<td>South Pacific Islands</td>
<td>LF (<em>W. bancrofti</em>) and dengue</td>
<td>(12)</td>
</tr>
<tr>
<td></td>
<td><em>Ae. scapularis</em></td>
<td>North and South America</td>
<td>LF (<em>W. bancrofti</em>)</td>
<td>(12)</td>
</tr>
<tr>
<td></td>
<td><em>Ae. pseudoscutellaris</em></td>
<td>South Pacific Islands</td>
<td>LF (<em>W. bancrofti</em>) and dengue</td>
<td>(12,21,22)</td>
</tr>
<tr>
<td></td>
<td><em>An. culicifacies, An. stephensi, An. fluviatilis</em></td>
<td>India/Western Asia</td>
<td>Malaria</td>
<td>(4)</td>
</tr>
<tr>
<td><em>Culex</em></td>
<td><em>Cx. tritaeniorhynchus</em></td>
<td>Southeast Asia and the Pacific, Africa, Middle East</td>
<td>JE, Rift Valley fever, Murray Valley encephalitis virus</td>
<td>(24,25)</td>
</tr>
<tr>
<td></td>
<td><em>Cx. quinquefasciatus</em></td>
<td>North, Central and South America, Southeast Asia</td>
<td>LF (<em>W. bancrofti</em>)</td>
<td>(12,23)</td>
</tr>
<tr>
<td><em>Mansonia</em></td>
<td>Various species</td>
<td>Asia and the Pacific</td>
<td>LF (<em>B. malayi</em>)</td>
<td>(12,23)</td>
</tr>
</tbody>
</table>

Abbreviations: *Ae.*, *An.*, *B.*, *CHIKV*, *CHIKV*, *Culex*, *JE*, *LAI*, *W.*; CHIKV, chikungunya virus; *Cx.*, *Culex*; JE, Japanese encephalitis; LF, lymphatic filariasis; *W.*, *Wuchereria*; YF, yellow fever, ZIKV, Zika virus

¹ Species that have recently established in Canada (20)
² Species that are established in Canada (19)
³ Species (*An. funestus* and *An. gambiae*) that transmit both malaria and LF (*W. bancrofti*)
⁴ 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, viremic humans and/or viremic 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).
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.

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

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

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

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

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*Note: The association between exotic mosquito-borne diseases and climate change is non-linear and is influenced by other contextual factors.
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