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CLIMATE CHANGE AND INFECTIOUS DISEASES: THE SOLUTIONS

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An innovative approach to address the health effects of climate change is through the prediction and early detection of infectious disease outbreaks. One way this can be done is with the use of satellite data. This is a Shutterstock photo with elements from the National Aeronautics and Space Administration (NASA), adapted by Lyal Saikaly. (https://www.shutterstock.com/image-illustration/satellite-orbiting-around-earth-elements-this-238055446).

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The health effects of climate change: Know the risks and become part of the solutions

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Abstract

Climate change presents a clear and present danger to human health. Health impacts are already being demonstrated in Canada, which is warming at roughly twice the global rate. A recent United Nations *Environment Emissions Gap Report* noted that if countries maintain current emission efforts, emissions will exceed the targets laid out in the Paris Agreement and global warming will exceed 2°C worldwide. An important consequence of global warming is an increase in health risks. Much can be done to prevent and mitigate the health impacts of climate change, and understanding and communicating these has been shown to be one of the best ways of motivating action. This editorial provides an overview of the some of the global and national initiatives underway to decrease emissions, and address the health risks of climate change in general, and highlights some of the national initiatives underway to mitigate the increased risk of infectious diseases in Canada in particular.

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Keywords: climate change, health impact, infectious diseases, resilience, adaptation, prevention, emissions, eco-anxiety, ecological grief, mosquito-borne diseases, surveillance

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Introduction

The World Health Organization has stated that "Climate change is the greatest challenge of the 21st century, threatening all aspects of the society in which we live" (1). To address this challenge, 175 countries have ratified the Paris Agreement within the *United Nations Framework Convention on Climate Change* (2). Collectively, these countries agreed to limit global average temperature rise to well below 2°C, and to pursue efforts to limit the increase to 1.5°C. Canada is a signatory to the Paris Agreement and has committed to cut emissions to 30% below 2005 levels by 2030. Unfortunately, in 2016 Canada's emissions had actually increased compared with 1990 (3). Although some countries have made great progress (notably, the United Kingdom and China), the 2018 United Nations *Environment Emissions Gap Report* noted that if all signatory countries maintain current emission efforts, emissions will exceed the targets laid out in the Paris Agreement, and global warming will exceed 2°C (4).

To respond to the need to reduce emissions and build climate resilience, the Government of Canada, after extensive consultations with provinces, territories and Indigenous Peoples, developed a national climate change plan. *The Pan-Canadian Framework on Clean Growth and Climate Change* was adopted by most of the Canadian First Ministers in December 2016 (5). The Framework notes the science is clear: human activities are driving unprecedented changes in the Earth's climate, which pose significant risks to communities, human health, security, economic growth and the natural environment. It notes that the impacts of climate change are already evident in that there is already documented coastal erosion, thawing permafrost, the arrival of diseases that had previously been contained to warmer climates, increases in heat waves, droughts and flooding as well as risks to critical infrastructure and food security (5). The plan to address this in Canada was developed around four pillars: pricing carbon pollution; complementary actions to reduce emissions across all sectors; adaptation and resilience; and clean technology, innovation and jobs. The Framework includes more than fifty concrete actions and positions by which Canada aims to meet its Paris Agreement greenhouse gas emissions reduction target by 2030. For example, carbon pollution pricing systems and benchmarks have been established across Canada.

Although annual reports on this Pan-Canadian Framework have documented important progress (6), there is still a gap between where we are and where we need to be so that Canada can meet its targets. The recent 2019 *Canada's Changing Climate Report*, produced by Environment and Climate Change Canada, noted that Canada is currently warming at twice the mean global rate, with the Canadian Arctic warming, on average, at triple the global rate (7). For example, the McKenzie Delta region is already 3°C warmer than in the 1950s (8).

The health effects of climate change

Meeting our emission commitments is not a theoretical "nice to have". There is a growing awareness that climate change is leading to emerging health threats. Internationally, efforts such as the Lancet *Countdown on Health and Climate Change*, have made clear that some of the top health threats worldwide include heat-related adverse effects on health and work productivity, worsening markers of food security, and intensifying infectious disease impacts.

There is growing evidence of climate-related health threats in Canada. With rising temperatures in the north, land-based food security has been threatened for Indigenous populations (9,10), the safety of ice-based travel has been reduced and mental health has been strained (11). Climate-related health risks across Canada include increased heat stroke and death from the increased number and duration of heat waves (12,13); and respiratory impacts from wildfire-related air pollution (14). Extreme wildfires are expected to continue to increase (7), leading to episodes of severe air pollution and increased stresses on healthcare facilities and healthcare providers (as was seen during the emergency evacuation of the hospital in Fort McMurray in 2016). Similarly, floods are forecast to increase, bringing about their own risk of damage to property and the associated personal and societal disruption from evacuation. Anxiety and post-traumatic stress disorder-type symptoms have been experienced by those who have been affected by fires, floods and extreme weather events (15). New terms, such as eco-anxiety and ecological grief are now entering the lexicon (16). Infectious disease risks of climate change in Canada were detailed in the April 2019 issue of Canada Communicable Disease Report, and included an increased risk of tick-borne diseases (17), endemic and exotic mosquito-borne diseases (18,19), as well as foodborne diseases (20).

Understanding the health impacts of climate change has been shown to be one of the best ways of motivating action (21), and health professionals and scientists are among the most trusted of messengers (22). In this editorial, we highlight some recent global and national initiatives to address both climate change and its health effects in general, and then highlight the work described in this issue on initiatives to address emerging infectious disease risks in particular.

Global initiatives

The recent Lancet *Countdown on Health and Climate Change* noted health professionals and health systems are increasingly considering and responding to the health effects of climate change (23). And for good reason: a better understanding of the health dimensions of climate change allows for advanced preparedness, increased resilience and adaptation and a prioritization of mitigation interventions that protect and promote human wellbeing (23).

The World Health Organization has been working on a new report entitled *Global Strategy on Environment, Climate Change, and Health* (24). The draft *Global Strategy* calls for an integrated approach for public health and environment science to intensify work on primary prevention and advance policies that address the root causes of environmental threats to health. The World Health Assembly is expected to approve this new strategy in May 2019.

Adaptation is about reducing the impacts associated with a given level of climate change. In October 2018, a new *Global Commission on Adaptation* was announced and is being led by former United Nations Secretary-General Ban Ki-moon, American businessman Bill Gates and World Bank Chief Executive Officer Kristalina Georgieva (25). The report will demonstrate why adapting to climate risks is essential, and will lay out the actions that are needed. The Commission will present its report at the United Nations Climate Summit in September 2019 in New York.

Globally, there is a youth movement calling for action on climate change, sparked by the 16-year old Swedish activist, Greta Thunberg (26). On March 15, 2019, 1.5 million youth, and their supporters in 123 countries, demonstrated around the world, demanding a significant response to climate change following an open letter to world leaders that stated: "You have failed us." (27), In Montreal alone, there were an estimated 150,000 demonstrators (28).

Canadian initiatives

The health effects of climate change in Canada have not gone unnoticed by healthcare professionals. In February 2019, the Canadian Medical Association, Canadian Nursing Association, Canadian Public Health Association, Canadian Association of Physicians for the Environment and the Urban Public Health Network issued a Call to Action, identifying climate change as a health emergency (29). The Canadian Federation of Medical Students and the International Federation of Medical Students' Associations have both called for climate-health to begin to be integrated into medical education by the end of 2020, with fuller integration by 2025 (30). Without it, health professionals may not be prepared for the climate-related health issues that they are bound to see currently in their practices and in the years ahead.

Canada is on track to phase out coal power by 2030; a policy that is expected to result in $1.3 billion in health and environmental benefits from air quality improvement (31). Canada has now co-founded the Powering Past Coal Alliance with the United Kingdom in an effort to catalyze international efforts (32) that could multiply these health benefits. Equally, the new Food Guide for Canada, with its emphasis on a plant-rich diet, is likely to result in a decrease in the greenhouse gas emissions that result from the production and consumption of animal-based foods. This is in line with the recommendations of the recent EAT-Lancet Commission that identifies benefits for both human and planetary health (33,34).

Much change is also possible at the community level. In terms of sustainable transportation, physicians and public health practitioners have become more active in encouraging active transport infrastructure in multiple communities to decreases emission rates and improve health (35). Vancouver's commitment to be one of the most sustainable cities in the world contains many elements that will increase activity levels and decrease air pollution (36). Getting people out of fossil fuel-powered cars and into more sustainable forms of transport, such as bicycles and buses, not only reduces emissions, it also reduces local air pollution, improves activity levels and reduces disease.

Addressing the increased risk of infectious disease

In this issue of the Canada Communicable Disease Report, you will read about how government and academic researchers in Canada have been finding solutions to address the increased risk of infectious diseases with climate change. A key focus has been early detection and prevention strategies. Rees et al. describe a new generation of surveillance strategies for the prediction and early detection of climate-related infectious disease outbreaks, namely risk modelling and event-based monitoring that uses open-source internet data, which has recently been refined by artificial intelligence applications, such as machine learning (37). Ogden et al. note that since warming, climate variability and extreme weather events drive the increase in the frequency and intensity of mosquito-borne diseases, understanding the associated weather patterns can provide early warning of when a region is at risk. Timely information on an impending outbreak can enable the implementation of mosquito control measures and risk communications—before an outbreak occurs (38). Kotchi et al. note that satellite images can provide data on indicators of environmental and climatic determinants that influence the presence and development of mosquito-borne and tick-borne diseases. Thus, data on change in temperature, humidity, ground cover and more can be used to predict infectious disease outbreaks. Work is now underway to increase predictability of this technique by using data from multiple satellites and applying innovative machine learning techniques to deal with big data (39). Germain et al. describe a new collaborative model among scientific experts and public policy makers across the province of Quebec in a "One World, One Health" organizational structure that provides a platform for knowledge-sharing, consensus-building and the development of adaptive strategies to address the increased risk of zoonotic diseases associated with climate change (40).

Discussion and conclusion

A December 2018 poll by Ipso Reid showed that the majority of Canadians agree that Canada needs to do more to address climate change (41). But awareness of the health effects of climate change is not yet widespread. It is important for all Canadians to know that climate change is increasingly affecting health in a number of ways. Health and public health providers have an important role to play in increasing the public awareness of these climate change-associated health risks. There is a positive message that can be imparted: a better understanding of the health effects of climate change enables increased preparedness, resilience, adaptation, and the development of strategies that protect and promote human health. And a lot of work is underway to address the health effects of climate change in the context of adaptation. These are focused on preparedness, prevention and resilience. It includes a whole new generation of strategies to detect when we are at increased risk of climate-associated infectious diseases.

Health and public health providers need to be ready to play an active role in the prevention, early detection and mitigation of the health effects of climate change. To do that, climate and health content needs to be increasingly included in curricula and in continuing education courses. The adverse effects of air pollution and the traumatic effects of extreme weather events are fairly obvious and well-documented. But the effects of climate change on emerging infectious disease risks in Canada are less evident and less well-known. In order not to miss climate-change induced emerging vector-borne diseases in affected people, a high index of suspicion and laboratory confirmation is needed. Understanding and staying abreast of the new strategies for the early detection of emerging disease risks and outbreaks that will likely be driven by a changing climate, will help health and public health professionals be prepared and respond.

Knowing the risks and being part of the solutions are healthy responses to climate change. There is a lot being done and a lot each healthcare professional can do to create a viable future for current and future generations. And that effort is worth it; to cultivate individual, family and community preparedness and resilience, to contribute to something larger than yourself–and because the world is watching.

Authors' statement

Both authors developed the overall conception and design of the editorial. PH developed the first draft and both CH and PH worked on subsequent drafts and revisions.

Dr. Courtney Howard is the President of the Canadian Association of Physicians for the Environment. Dr. Patricia Huston is the Editor-in-Chief of the Canada Communicable Disease Report and recused herself from taking any editorial decisions on this manuscript. Decisions were taken by the Guest Editor of the April 2019 issue, Dr. Nicholas Ogden.

Conflict of interest

None.

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Risk assessment strategies for early detection and prediction of infectious disease outbreaks associated with climate change

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Abstract

A new generation of surveillance strategies is being developed to help detect emerging infections and to identify the increased risks of infectious disease outbreaks that are expected to occur with climate change. These surveillance strategies include event-based surveillance (EBS) systems and risk modelling. The EBS systems use open-source internet data, such as media reports, official reports, and social media (such as Twitter) to detect evidence of an emerging threat, and can be used in conjunction with conventional surveillance systems to enhance early warning of public health threats. More recently, EBS systems include artificial intelligence applications such machine learning and natural language processing to increase the speed, capacity and accuracy of filtering, classifying and analysing health-related internet data. Risk modelling uses statistical and mathematical methods to assess the severity of disease emergence and spread given factors about the host (e.g. number of reported cases), pathogen (e.g. pathogenicity) and environment (e.g. climate suitability for reservoir populations). The types of data in these models are expanding to include health-related information from open-source internet data and information on mobility patterns of humans and goods. This information is helping to identify susceptible populations and predict the pathways from which infections might spread into new areas and new countries. As a powerful addition to traditional surveillance strategies that identify what has already happened, it is anticipated that EBS systems and risk modelling will increasingly be used to inform public health actions to prevent, detect and mitigate the climate change increases in infectious diseases.

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Keywords: climate change, risk assessment, event-based surveillance systems, artificial intelligence, machine learning, natural language processing, risk modelling

Introduction

Climate warming trends have been accelerating over the last few decades. The world's nine warmest years in the time period from 1850 to 2017 have all occurred in the last twelve years, with a total increase of approximately 0.97°C in the average annual air temperature for the time period from 1880 to 2017 (1). This ostensibly small increase in average global temperature is nevertheless responsible for significant changes in the worldwide weather patterns and associated effects on society through sea level rise (and associated erosion) and increased frequency and intensity of flooding, droughts (with associated wildfires and crop failures) and freezing rain events (2). Of particular importance to Canada, climate warming is even more acute at higher latitudes and in the winter months (3). Over the past 70 years, the overall annual average temperature in Canada has increased by 1.8°C (4), with an average winter temperature increase of 3.4°C (4). In some areas in the northwest, this increase has been even higher. Because climate change affects not only temperatures but precipitation patterns, Canada is experiencing generally drier conditions in the west and above average precipitation in the east (4).

Climate-driven changes to temperature and precipitation are known to affect the risk of infectious disease transmission. Climate change is modifying range distributions of disease vectors (i.e. ticks and mosquitoes) and reservoir populations (i.e. birds, rodents and deer) that participate in the transmission of pathogens from ticks and mosquitoes to humans as climate suitability for vector and reservoir populations change (5,6). For example, the increase in cases of Lyme disease in Canada reflect the northward expansion of the range of the black-legged tick vector, *Ixodes scapularis*, in the United States (US) and into southern Canada, as climate change has made Canada more conducive to establishing tick populations (7,8). This expansion of the area where the vectors and their reservoirs can thrive means not only an increased risk of sporadic infectious disease but also an increased likelihood that these vectors, and the diseases that they carry, can become endemic (6,9–11).

In addition, climate change is influencing the mobility patterns of people and goods. An increase in "climate refugees", people displaced when their lives and/or livelihoods are at risk from extreme weather events, is expected (11). Refugees, often from geographical areas where infectious diseases are more common and with different vaccination schedules and practices, may inadvertently bring these diseases into Canada (12). Tourism is also affected by climate change, as changes in both home and travel destinations influence the push and pull of factors motivating people to travel and the potential for disease spread (13–15). Vectors and pathogens can inadvertently be transported through shipments by air, land and sea (16–18). Land and sea containers are known to support the invasion of mosquitoes because larva can develop in trapped standing water, and if no water exists, eggs can withstand desiccation for weeks to months (19,20). Air travel has also been responsible for travellers carrying infections into new areas. In Canada, returning travellers have brought with them the Zika virus and have also sparked an outbreak of severe acute respiratory syndrome (SARS) coronavirus (15,21,22).

Thus, the increased risks of infectious diseases with climate change pose important public health risks and work is underway to monitor, assess and predict the impact of these risks. In the past, public health management has depended on notifiable disease reporting surveillance systems to detect outbreaks, monitor disease progression and inform prevention and mitigation policies. However, traditional surveillance systems are typically characterized by delays in the reporting and analysis of the data and the communication of the results.

To address the need for closer to real-time surveillance of emerging issues and earlier insight on potential health impacts, two risk assessment strategies have been, and are being, developed: event-based surveillance (EBS) systems, which increasingly incorporate artificial intelligence; and risk modelling. The objective of this overview is to describe these two risk assessment strategies and how they can inform public health actions to prevent, detect and mitigate the climate change increases in infectious diseases.

Event-based surveillance systems

Event-based surveillance systems use a variety of open-source internet data and assessment techniques to identify disease threats (23,24). Typical open-source internet data include online newswires, social media and other internet data streams, in multiple languages, to detect early-warning signals of threats to public health. These systems have proven to be more timely in comparison with conventional surveillance data sources from laboratory results or hospitals (25), and can be used in conjunction with conventional surveillance systems to enhance early warning of public health threats (26). The more quickly signals from an evolving outbreak are identified, the more quickly the outbreak can be tracked and a public health response can be planned and implemented (27).

There are three types of EBS systems: moderated; partially moderated; and fully automated (28). The level of automation influences how the information flow in EBS systems is managed from the open-source internet data from news aggregators (e.g. Factiva, Google News, Moreover Baidu), Rich site summary (RSS) and social media feeds from official and unofficial sources (e.g. Twitter for US Centers for Disease Control and general public), and validated official reports (e.g. World Health Organization, US Centers for Disease Control). The Program for Monitoring Emerging Diseases (ProMED) is an example of a moderated system and was on the forefront of EBS development over 25 years ago (29,30). ProMED is run by volunteer analysts (who are expert curators) who monitor and choose news articles, validate the content and notify subscribers of noteworthy infectious disease events. Strengths of this system include having a low signal-to-noise ratio, being open access and having a broad reach. However, volunteers do not cover all populations at risk, volunteer biases can influence the moderation of events and volunteers do not have the resources (nor are they expected) to provide detailed information giving situational awareness for assessing the threat level (29).

The Global Public Health Intelligence Network (GPHIN) is a partially moderated system that was developed by the Government of Canada, in collaboration with the World Health Organization, four years after ProMED (31–33). GPHIN access is restricted to agencies with health-related mandates. Artificial intelligence (AI) algorithms in GPHIN automate a stream of two to three thousand news articles per day that are moderated by 12 expert analysts who identify and issue alerts for threats using tacit contextual information (e.g. historic context, market trends, travel bans and climate anomalies). An example of the usefulness of GPHIN dates back to early 2003 when analysts identified reports from China referring to increased sales of antiviral therapies just before the global onset of the SARS epidemic (34). Unlike ProMED, GPHIN benefits from multi-staged filtering using AI and trained analysts. Artificial intelligence enables processing of a larger data stream, and analysts have the resources to provide information for situational awareness. Both ProMED and GPHIN can function in multiple languages; however, it is expensive for GPHIN to add in other languages because of the cost to hire analysts with language fluency (33).

Fully automated systems include the European Commission's Medical Information System (MedISys), Pattern-based Understanding and Learning System (PULS) and HealthMap. These systems are open to the public, but also have restricted access to serve the needs of health agencies such as private discussion forums, increased functionality and data processing of commercial sources (35,36). Fully automated systems are faster at processing data and less expensive to operate than moderated systems. The main drawback is the higher signal-to-noise ratio meaning that there is an increased risk of identifying false threats (37,38). The EBS systems can be connected in synergistic ways to address this risk (39). For example, MedISys uses low signal-to-noise ratio data from ProMED and GPHIN, and uses more advanced language processing algorithms from PULS. The PULS extracts information about events identified in the MedISys stream and then returns these data back to MedISys (36,40). The different types of EBS systems are summarized in **Table 1**.

Table 1: Summary of some event-based surveillance systems

Type	Example	Establishment	Public availability
Moderated system[a]	Program for Monitoring Emerging Disease (**ProMED**) (29,30)	In 1994 as a nonprofit organization	Yes
Partially moderated system[b]	Global Public Health Intelligence Network (**GPHIN**) (31–33)	In 1998 through partnership between the Government of Canada and World Health Organization	No; available to partnered health agencies
Fully automated system[c]	Medical Information System (**MedISys**) (36,41,42)	In 2004 by the European Commission	Yes
	HealthMap (35,38,40,43)	In 2006 by Boston Children's Hospital	Yes
	Pattern-based Understanding and Learning System (**PULS**) (36,44,45)	In 2007 by the Department of Computer Science, University of Helsinki, Finland	Yes

[a] A moderated system: volunteer expert-curators identify, review and validate sources and create the reports
[b] A partially-moderated system: automatically acquires, categorizes, and filters sources. Expert-curators moderate the subset of sources and create the reports
[c] A fully-automated system: automatically acquires, categorizes, filters and reports the health-related sources

Artificial intelligence applications

The ability of EBS systems to quickly and accurately detect threats (such as outbreaks of infectious diseases) has been revolutionized by artificial intelligence applications for data processing. Open-source internet data are considered "unstructured" in the sense that news articles, blogs, tweets, etc., provide a narrative describing an event. The text, numbers and dates are not organized in a data model, such as a database, that can be used for automated event detection and risk modelling; therefore, open-source data must be processed to extract and structure information about what happened, where it happened, when it happened and to whom it happened. The EBS systems use natural language processing (NLP) methods to process and understand event narratives (46–48). Natural language processing is a field of research dedicated to understanding human discourse (49). Early methods include the sub-language approach, where rules and patterns are used to interpret and classify vocabulary, syntax and semantics of the unstructured narrative. The EBS systems have taxonomies of terms to match predefined terms and their synonyms to those found in the data sources. Much like with a conventional literature search, taxonomic classification of narratives can identify health-related articles by searching for related terms (e.g. human influenza A synonyms include H1N1, swine flu, California flu, human influenza and influenza A) (50). The sublanguage approach for identifying health-related data in EBS systems is effective but also has drawbacks. Taxonomies are not easily generalizable and must be developed for each disease being monitored and kept up-to-date as language evolves and new discoveries about diseases are made. In this light, NLP has established a strong foundation in using machine learning (ML) methods.

Machine learning is a subset of AI that uses algorithms, such as statistical models, to perform a specific task without using explicit instructions; instead, relying on patterns and inference. The EBS systems gather open-source internet data (feeds and web queries) and then filter these data through a combination of the sublanguage approach and ML methods, where the latter is used to perform more complex tasks for analysing syntax, semantics, morphology, pragmatics and discourse (51). For example, ML methods can be used to determine the difference between non-health related articles (e.g. "Bieber fever" refers to avid supporters of Justin Bieber) and those discussing an infectious disease outbreak (43,51,52). Machine learning methods can also be used to distinguish between ambiguities in dates and locations, such as past and present outbreaks in articles that discuss historical context (53,54). Novel applications for ML methods are also being developed, such as structuring disease case information into epidemiological line lists (a listing of individuals affected by the disease and related information; i.e. health status, sex, location, date of onset, hospitalized) that can be used in outbreak investigations and risk modelling (55). Once the information from open-source internet data has been processed into a data model, the event can then be reviewed and reported, as appropriate; furthermore, additional data

Table 2: Information flow from open-source internet data in event-based surveillance systems

EBS	Data collection	Data processing	Data analytics	Reporting
Moderated systems	Human analysts search and identify open-source internet data for health-related concern	Human analysts review, filter and designate the threat level of the event	None	Reports on health-related threats are communicated through email and posted on EBS system website
Partially moderated and fully automated systems	Automated feed of open-source internet data	Taxonomic classification and ML algorithms filter and classify events based on their metadata (e.g. type of threat, location and date). ML algorithms score the level of relevancy. In partially moderated systems, highly scored data sources are curated by human analysts	Analytic techniques evolve with time and differ among EBS systems. Current techniques include the following: mapping of geo-tagged events; bar plots showing changes over time to keyword counts, number of identified articles and expected and observed number of disease cases; word clouds showing importance of keyword terms; alert notices given sudden increases to case counts, reliability of sources and/or number of unique sources	Reports on health-related threats are communicated through email and posted on EBS system website and notified to appropriate web application user communities

Abbreviations: EBS, event-based surveillance; ML, machine learning

analytics can be performed to communicate the current and predicted impact of the health threat. A summary of information flow from data collection, processing, analytics and reporting for EBS systems is presented in **Table 2**.

Risk modelling

An important advancement for risk assessment is increasing the variety of data being used in modelling approaches. Risk modelling in the context of infectious diseases is the process of identifying and characterizing factors in individuals or populations that increase their vulnerability to contracting disease (e.g. age, proximity to outbreak). Statistical inference is a well-grounded and informative risk modelling approach that includes regression analysis. This method is used to determine how risk factors (explanatory variables) are associated with the outcome of interest (e.g. number of reported cases). Regression models, and statistical inference in general, are developing to include information from open-source internet data. An early example was the inclusion of search query engine data from Google Flu Trends as a predictor for the outcome of the number of reported physician visits for flu-like illnesses (56). The resulting model was then used to predict the number of seasonal influenza cases one to two weeks into the future; however, this approach was not as effective in predicting outbreaks outside of the traditional flu season because of associations being identified with search query trends not related to seasonal influenza (e.g. winter basketball season) (57). Subsequent work improved the accuracy of predicting seasonal influenza flu trends by using additional sources of open-source data (e.g. Twitter) and expanding the regression method to benefit from ML algorithms that can find complex associations among the outcome and explanatory variables (58). Furthermore, regression modelling for the risk of infection has improved by including, in addition to open-source internet data, additional explanatory variables (e.g. climate and meteorological data from satellite imagery) that account for the presence, movement and distribution of pathogens, vectors, reservoir populations and infected people (59,60). For example, in China, the expected number of cases of hand, foot and mouth disease in children was best predicted by including data on weekly temperature and precipitation as well as data on hand, foot and mouth disease-related queries from the Chinese Baidu search engine (61).

Another dominant risk modelling approach is the use of compartmental models to mathematically simulate transmission dynamics of a population; that is, the flow of individuals among health states, such as susceptible (S), infectious (I) and recovered (R). For example, SIR models require defining parameters for the infectious rate (or inversely, the infectious period) and the rate of infectious contacts. It is then possible to estimate if an infected population will become epidemic, and to characterize the prevalence of a disease over time. The compartmental modelling approach has more recently developed to simulate transmission dynamics among multiple populations (meta-populations). This requires the inclusion of mobility data to define the rate of individuals moving among populations (62). Human mobility at a meta-population level can be considered as the movement of people in a connected network of cities and countries. These data can be obtained from mobile phone call records and air traffic passenger volumes (63,64). Through meta-population modelling, it is possible to identify the travel routes through which pathogens may spread or be carried to Canada, as well as to determine the likelihood of these events (65,66). For example, the Zika virus is estimated to have first appeared in Brazil between August 2013 and April 2014 by infected travellers entering the country at Rio de Janeiro, Brasilia, Fortaleza and/or Salvador; and this introduction was followed by epidemics in Haiti, Honduras, Venezuela and then Colombia (21).

Discussion

There is uncertainty as to how climate change will affect the many factors related to the occurrence and spread of infectious diseases. These factors will undoubtedly include changes to the distributions of vector and reservoir populations, and changes to the mobility of people and goods and potential transport of pathogens, with subsequent impacts on exposure and transmission risks. To monitor infectious disease outbreaks in an effective and timely manner, public health professionals need better access to up-to-date surveillance data. To achieve this, conventionally-obtained data, such as that from existing notifiable disease reporting surveillance systems, are increasingly being augmented by EBS systems. The EBS systems are benefiting from ML and NLP methods to more fully exploit the available data; however, challenges remain (59). There are issues of data sharing and privacy that need to be resolved. For example, at what level can personal data be used and disclosed in the detection of health-related events? Both Google and Twitter provide their data freely to the public as finely aggregated per week and city; however, more precise information on the timing and location of the source would enable more comprehensive event detection (26). Also, there are differences where and how people use the internet and social media around the world: there are gaps in internet and mobile phone use in Africa (67); Baidu, rather than Google, is the predominant search engine in China (61); and the propensity of people using Twitter to report illnesses is dependent on age and socioeconomic status (68).

Risk modelling provides a means of estimating the health impacts of emerging infectious diseases. Advances in risk modelling approaches include integrating open-source internet and climate data to inform these estimates, and accounting for the mobility of humans to spread infectious diseases globally. As with EBS systems, risk modelling approaches are limited by the availability of the data that can be obtained. For example, mobile phone call records and air traffic data provide information to the nearest cell phone tower and airport respectively, but more precise location data are available, granted privacy concerns, through the global position system in mobile phones. Information at the individual level could greatly increase our understanding of the factors affecting disease occurrence and pathogen spread, for example, the role of certain people to drive the 2003 SARS outbreak (69).

Conclusion

Advances in assessing changes to vector and reservoir populations and human activity, and their impacts on infectious diseases, are now being monitored by a number of different surveillance and analytical strategies. Event-based surveillance systems use open-source data to gather information relating to infectious diseases. These systems can be moderated, partially moderated or fully automated, and each type of system has advantages and disadvantages. There is a growing trend towards automation because of the ability to process high volumes of data, and the accuracy of ML and NLP methods to identify events are improving and may one day surpass the ability of human moderators. Risk modelling to understand and predict the health impacts of infectious diseases is commonly performed using statistical inference and compartmental modelling approaches. These methods are advancing the ability to identify populations at risk to emerging diseases, and forecast health impacts and determine pathways of disease spread by integrating open-source internet data and human mobility data, along with more traditional data variables from climate data and infectious disease outbreak data. The methods we have presented here are promising new developments that will increase our capacity to deal with evolving disease threats as the climate changes. Having more information (and more accurate information) sooner will make it possible for public health professionals to confirm and evaluate potential infectious disease outbreaks faster and thus to develop and commence treatment and other mitigation strategies in a more timely fashion.

Authors' statement

EER — Conceptualization, investigation, writing—original draft, supervision and project administration
VN — Investigation, writing—review and editing
PG — Writing—review and editing
AM — Writing—review and editing
DM — Writing—review and editing
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Conflict of interest

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Weather-based forecasting of mosquito-borne disease outbreaks in Canada

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Abstract

Early warning systems to predict infectious disease outbreaks have been identified as a key adaptive response to climate change. Warming, climate variability and extreme weather events associated with climate change are expected to drive an increase in frequency and intensity of mosquito-borne disease (MBD) outbreaks globally. In Canada, this will mean an increased risk of endemic and emerging MBD outbreaks such as West Nile virus and other MBDs. The availability of timely information on the risk of impending MBD outbreaks has important public health implications, by allowing implementation of mosquito control measures and targeted communications regarding the need for increased personal protective measures—before an outbreak occurs. In Canada, both mechanistic and statistical weather-based models have been developed to predict West Nile virus outbreaks. These include models for different species of mosquitoes that transmit West Nile virus in different geographical areas of Canada. Although initial results have been promising, further validation and assessment of forecasting skill are needed before wide scale implementation. Weather-based forecasting for other emerging MBDs in Canada, such as Eastern equine encephalitis, may also be feasible.

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Keywords: mosquito-borne diseases, weather-based forecasting, West Nile virus, Eastern equine encephalitis, climate change, Canada

Introduction

The United Nations Intergovernmental Panel on Climate Change has identified the development of early warning systems as a key adaptation strategy to deal with the health risks of climate change (1). One type of early warning system is weather-based forecasting, or the use of weather data to predict the risk of a specific infectious disease outbreak in a specific area. Research on a wide range of mosquito-borne diseases (MBDs), including West Nile virus (WNV), malaria and Rift Valley fever, have proven the concept of weather-based forecasting (2). The United States' (US) National Oceanic and Atmospheric Administration has initiated a program to facilitate validation of various forecasting models (3).

In Canada, the most common MBD is the West Nile virus infection. This virus is endemic in the southernmost parts of Canada and human cases have been detected across much of the country. The WNV causes a range of mild to severe illness, and occasionally deaths, each year (4). Other MBDs, including the California serogroup viruses (snowshoe hare virus and Jamestown Canyon virus) and Cache Valley virus, are endemic in Canada. There is some evidence that not only may these MBDs be more common in humans in Canada than previously thought (5,6) but they may also increase with climate change (7). In addition, there is increasing concern that other MBDs, which are currently endemic in the US, may expand northward into Canada with climate change (8). Furthermore, there will be an increased risk that exotic MBDs, such as dengue and chikungunya—and the mosquitoes that carry them—will become established in Canada. With climate change, these exotic mosquitoes, having been introduced from abroad via increased international passenger travel and increased international shipping, may now find the environmental conditions that they need to survive (9).

Globally, many MBDs demonstrate epidemic behaviour (10). This "boom and bust" epidemiological pattern is also seen with WNV in Canada. This means there are epidemics of WNV in some years and only small numbers of cases in other years. In 2007, 2,215 cases were reported (mostly from an outbreak affecting the prairie provinces) and in 2010, only five cases were reported and in 2012, 428 cases were reported (mostly from an outbreak affecting Ontario and Quebec) (4). This epidemic behaviour is thought to be due mostly to the effects of the weather on mosquito lifecycles and WNV transmission. In 2007, a mild winter followed by a warm and wet spring provided ideal weather for multiplication of *Culex tarsalis* (the main WNV vector in the Prairies), while hot summer weather in eastern Canada in 2012 may have enhanced WNV transmission by *Cx. pipiens* and *Cx. restuans* (the main vectors in eastern Canada) (4).

The methods currently used to monitor WNV in Canada are mosquito surveillance (to detect the levels of environmental hazard), detection of infection in sentinel animals and human case surveillance (which also assesses the severity of the disease burden). The environmental hazard is the number of human-biting, infected mosquitoes present in a given area (4). Increases in both the number of infected mosquitoes and number of human cases typically occur in the late summer to early autumn (4). If these increases occur early in the season, or the increases in infected mosquitoes and/or human cases are higher than usual, it may indicate the start of an epidemic. When the signal of an increased WNV risk is identified, it triggers two local public health responses. The first response is mosquito control, including the use of larvicides and (where acceptable) adulticides (11), and the second response is public awareness, including the promotion of personal protective measures (12).

The drawback of the current WNV surveillance system is that it can detect outbreaks only after they have started. By understanding how weather affects mosquito lifecycles and virus transmission, it is theoretically possible to predict MBD outbreaks and enable a public health response to begin before an outbreak actually occurs (3,13).

The objective of this overview is to describe the concepts, methods and status of weather-based forecasting for WNV in Canada, and identify the next steps needed to implement forecasting as a public health tool.

Concepts of weather-based forecasting

Weather-based forecasting for MBDs uses knowledge of the influence of ambient temperature and precipitation on the survival and lifecycles of mosquitoes. For example, ambient temperature affects the rate of development of mosquito eggs, larvae and pupae, with warmer temperatures accelerating the mosquito lifecycle. Warmer temperatures also accelerate the extrinsic incubation period, or how fast mosquito-borne pathogens ingested by adult mosquitoes multiply and are disseminated from the gut to the salivary glands from whence they can be transmitted to humans (14). Higher temperatures can also affect the activity level of the adult mosquitoes. In addition to changes in temperature, changes in precipitation can also affect mosquito abundance. Excess precipitation often leads to standing water, and this can enhance mosquito replication, because standing water is required for the larval and pupal stages of the mosquito. As a further complication to weather-based forecasting, droughts turn drainage channels in urban and sub-urban areas into standing water, which then becomes mosquito breeding habitat. Therefore, some outbreaks in these areas are associated with dry as well as hot weather.

Weather-based forecasting looks for conditions associated with MBD outbreaks, and these conditions are particular to a specific mosquito, a specific MBD and a specific geographic area. **Figure 1** summarizes a hypothetical MBD outbreak, with and without the timely public health response informed by weather-based forecasting. Using conventional surveillance techniques, the delay between the beginning of an outbreak and confirmation of the outbreak can be one to four weeks (one week for testing of infected mosquito and four weeks for clinical diagnosis, laboratory testing and reporting of an infected patient) (Figure 1A). Thus, by the time the outbreak is confirmed, it is largely over. In contrast, Figure 1B shows the possible effects of an early (i.e. weather-based forecasting) response, which could trigger an early public health response, thereby reducing the number of infected mosquitoes and hence the severity of the MBD outbreak.

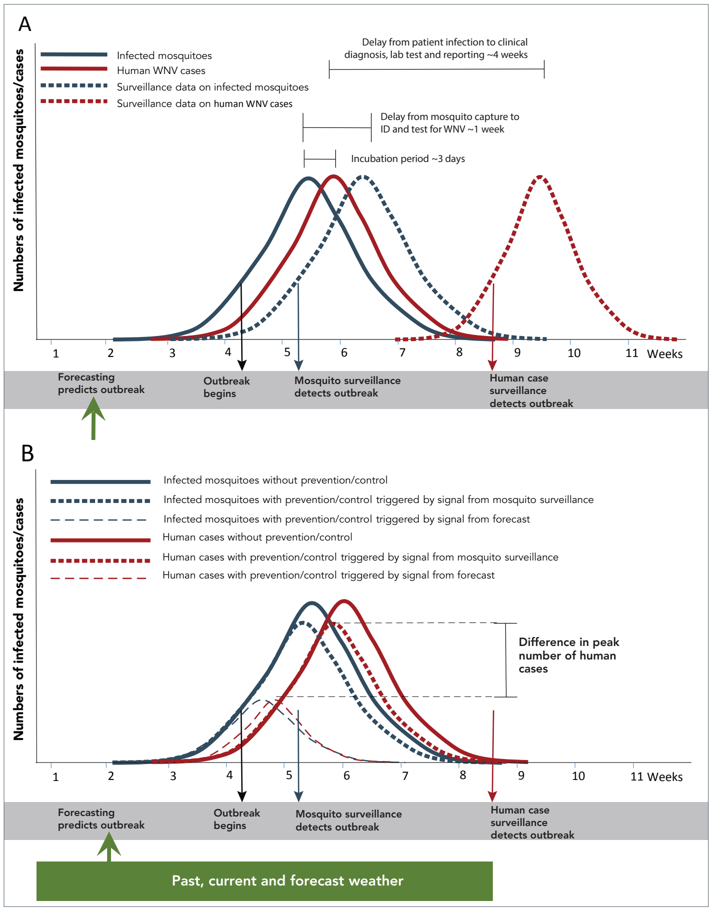
Types of forecasting models

Weather-based forecasting is done using either mechanistic or statistical models. The forecasting models that have been developed for Canada are described below.

Mechanistic models

The simplest mechanistic types of models are those that employ simple indices of temperature, obtained from laboratory studies, for key points of the mosquito lifecycle (e.g. limits for mosquito activity) or virus transmission cycles. One method (15), developed and implemented in Saskatchewan, uses a simple measurement of the accumulated days with temperatures above a threshold of 14.3°C, which is the threshold temperature for development of WNV in the prairie mosquito vector, *Cx. tarsalis*. These data are then used to estimate the timing of high risk to the public. Similar data are used in public information pieces by public health organizations in Quebec and Ontario, although these have not yet been assessed as early warning systems (16,17). Most mechanistic models are mathematical reconstructions of mosquito lifecycles and pathogen transmission cycles. These models incorporate known effects of temperature and precipitation on the mosquito lifecycle, and effects of

Figure 1: How weather-based forecasting facilitates an early public health response to a mosquito-borne disease outbreak



Abbreviations: ID, identify; WNV, West Nile virus
Figure legend: In panel A, the numbers of infected mosquitoes and human infections at the time they occur is shown by solid lines graph, and the numbers of infected mosquitoes and human infections at the time they are detected by surveillance systems is shown by dashed line graphs. The reasons for, and duration of, delays between occurrence and detection by surveillance are shown by horizontal lines. In panel B, the numbers of infected mosquitoes and human infections in the absence of public health intervention (shown by the solid line graphs), are compared against the numbers if interventions are started in response to signals from mosquito surveillance (shown by dotted lines) or by forecasting (shown by dashed line graphs). The black arrow indicates the start of an outbreak; the green, blue and red arrows indicate the signals of an outbreak provided by forecasting, and mosquito and human case surveillance respectively. The green rectangle indicates the past current and forecast weather used to develop the mosquito forecast

temperature on the extrinsic incubation period, to predict how recent and forecast weather may affect mosquito abundance and the proportion of these mosquitoes that will be infected in coming weeks to forecast the hazard to humans (18). For these models to be effective in predicting risk in a particular location, where prevention and control may have to be implemented, they need to be detailed, with many parameters involved in estimating weather-based and weather-independent influences on the mosquito lifecycles and pathogen transmission cycles. These models have been developed largely for forecasting exotic MBD outbreaks, such as malaria in Africa (19). In Canada, there is currently only limited detailed, quantitative knowledge of how temperature and rainfall affect different mosquito lifecycles.

Only one mechanistic weather forecasting model that uses reconstruction of mosquito lifecycles has been developed in Canada. Yu et al. developed a mechanistic model of the lifecycle of *Cx. pipiens* and *Cx. restuans* mosquitoes in eastern Canada (20), which incorporates data on the effects of temperature on mosquito development and survival. This model performed well against mosquito surveillance data used in its validation.

Statistical models

Statistical models use statistical "pattern matching" to identify how current and recent temperature and rainfall affect the abundance of mosquitoes and the proportion of these mosquitoes that are infected with pathogens (21,22). Pattern matching is developed with recent weather data and the current mosquito surveillance data to identify the quantitative relationship between the numbers of mosquitoes (and proportions of mosquitoes infected) on any one day and the accumulated or mean temperature and precipitation values for specific mosquito capture sites during the preceding weeks and months. Using this relationship, and taking into account the expected weather over the coming weeks (data that are obtained from weather forecasting models), the abundance of mosquitoes and proportion infected can be forecast (23).

In Canada, four weather-based forecasting statistical models for WNV have been developed, in the three regions of Canada where the risk is greatest: southern parts of the prairie provinces; southern Ontario; and southern Quebec. One model was developed in Saskatchewan to forecast both the numbers of *Cx. tarsalis* mosquitoes and the proportion infected in the Prairies, using temperature and precipitation data as predictors (23). This model was loosely validated against the numbers of human cases in two months of one year, and predicted a spatial pattern of risk for these two months that was consistent with the observed pattern of incidence of human cases. The other three statistical models have been developed in Quebec (22) and Ontario (21,24) where the vectors of WNV are *Cx. pipiens* and *Cx. restuans* mosquitoes. All models used temperature and precipitation data as predictors, and were validated against mosquito surveillance data (21,22,24). One of the Ontario models (21) has undergone a trial in the Toronto area by the Peel Region Public Health Unit (25). Both predicted and observed risks were low during the trial period.

Validation approaches

There are a number of different approaches to the validation of weather-based forecasting models. One approach is to compare the data from traditional surveillance methods (of mosquitoes, viruses and human cases) with model-predicted values obtained using mechanistic or statistical models based on local weather data. For the studies conducted in Canada to date, such entomological validation suggests that both the mechanistic and statistical modelling approaches to weather-based forecasting show great promise. There is evidence of spatial heterogeneity in how the mosquito populations respond to weather at a local scale. This is likely due to the modulation of temperature and/ or precipitation by local topography, resulting in changes in the habitat of immature mosquitoes (16,26). Accounting for variation in the topography improves the performance of the models (22–24).

A more public health-oriented approach to validation is an estimation of the probability that the model correctly predicts outbreak versus non-outbreak conditions (known as the "forecasting skill" of the weather-based forecasting model). The World Health Organization's aim for malaria forecasts is to have acceptable skill in forecasting 60% of malaria outbreaks over the subsequent two weeks (13). A number of metrics are used to define this acceptable skill, including those based on receiving-operator characteristic (27), which quantify the capacity of the model to have acceptable sensitivity (i.e. low false negatives—so will miss few outbreaks) and acceptable specificity (i.e. low false positive—so will raise few false alarms). The extent to which missed outbreaks and false alarms are tolerable is a decision of public health professionals and policy makers, who would ultimately decide on a model's public health utility.

Discussion

The Intergovernmental Panel on Climate Change has identified the need for early warning systems, such as weather-based forecasting, to detect MBD outbreaks. Several weather-based forecasting models have been developed in Canada for WNV, outbreaks of which are anticipated to become more frequent with climate change. Initial validation research suggests that these models show great promise. These models have the potential to provide short range forecasting of risk (i.e. of one or a few weeks ahead). This type of forecasting may be too short range to be useful in triggering proactive reduction measures to kill immature mosquitoes (larviciding), but would certainly allow for both reactive reduction measures to kill adult mosquitoes (adulticiding) as well as alerts to the public to enhance adoption of personal protection. Usually the rates of adoption of personal protection methods are low (28–30), in part, because of a perception of low risk by the public. Weather-based forecasting offers the possibility of raising awareness and heightening risk perception amongst the public, and so could increase adoption of personal protection measures at times and places where impending risk is high.

Weather-based forecasting of WNV would be a useful adjunct to our public health response to improve protection of Canadians from emerging and re-emerging MBDs by providing the earliest possible warning of outbreaks. However, there are limits to its application. First, this type of forecasting cannot replace surveillance in humans, mosquitoes and/or sentinel animals, as outbreaks can be due to factors independent of (or only indirectly associated with) weather. These factors include changes in herd immunity of wild animal reservoir host populations or emergence of novel strains of pathogens associated with MBDs (4). Maintaining mosquito surveillance is also prudent as it would allow for regular validation of forecasting models. Second, early signals of impending MBD risk, provided by forecasting models, demand that public health systems, methods and actions can respond rapidly to these risks, although in most jurisdictions this type of public health response is already in place.

Forecasting of WNV and other MBD epidemics on a national scale in Canada is a possibility for the future. Research needed before implementation includes prospective validation and assessment of forecasting skill (and how that may vary geographically), adoption and application by end users and the development of methods to best communicate this type of risk to the public. To achieve these aims will require resourced, concerted field, laboratory and computer simulation studies by local, provincial/territorial and federal organisations working in collaboration with entomologists, ecologists, epidemiologists and mathematicians in academic research institutions.

To date, weather-based forecasting has only been attempted for WNV in Canada as there is currently too little knowledge of the ecology of other MBDs endemic to Canada (e.g. the California serogroup viruses), and little systematic surveillance data with which to calibrate and validate models. But this may be possible in the future with more systematically collected data.

In general, weather-based models have greater forecasting skill over short time scales (i.e. the short term or extended forecasts of a few days to a week) (21), and decreasing forecasting skill over longer time scales (i.e. long range or seasonal forecasts of weeks to months) (31). However, some longer range forecast models have met the World Health Organization's target of 60% skill in forecasting (32). The weather-based forecasting models that have been most successful at forecasting on a seasonal timescale are those that aim to predict variations in the magnitude of the normal seasonal peaks of endemic MBD, such as malaria, when the magnitude of those peaks are determined by cyclical global climate phenomena, particularly the El Niño Southern Oscillation (33). This kind of forecasting has not yet been explored for WNV in Canada, in part due to the short (circa 10 year) time series of surveillance data (34).

Conclusion

The future implementation of weather-based forecasting of WNV, and potentially other MBDs, will allow for earlier alerts of impending outbreaks. As outbreaks of MBDs are anticipated to increase in frequency and/or intensity with climate change, these alerts will allow for more accurate and timely public health response with a concomitant reduction in public health impact. Adoption of the idea of weather-based forecasting, and more widespread practical implementation by public health in Canada, depends on further validation and assessment of forecasting skill, as well as exploration of the degree to which forecasting models need to be calibrated for specific geographic areas. Development of weather-based forecasting for other endemic and emerging MBDs should be possible with increased knowledge of the ecology of these diseases, and with more systematic surveillance.

Authors' statement

NHO led writing the article, NHO and AL conceptualized the article, all authors (NHO, AL, APM, LRL, HZ) contributed to drafting the paper.

Conflict of interest

None.

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Using Earth observation images to inform risk assessment and mapping of climate change-related infectious diseases

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Abstract

The number of human cases of several climate-related infectious diseases, including tick- and mosquito-borne diseases, has increased in Canada and other parts of the world since the end of the last century. Predicting and mapping the risks associated with these diseases using environmental and climatic determinants derived from satellite images is an emerging method that can support research, surveillance, prevention and control activities and help to better assess the impacts of climate change in Canada. Earth observation images can be used to systematically monitor changes in the Earth's surface and atmosphere at different scales of time and space. These images can inform estimation and monitoring of environmental and climatic determinants, and thus disease prediction and risk mapping. The current array of Earth observation satellites provides access to a large quantity and variety of data. These data have different characteristics in terms of spatial, temporal and thematic precision and resolution. The objectives of this overview are to describe how Earth observation images may inform risk assessment and mapping of tick-borne and mosquito-borne diseases in Canada, their potential benefits and limitations, the implications and next steps.

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Keywords: Earth observation images, climate change, risk mapping, infectious diseases, tick-borne diseases, mosquito-borne diseases, remote sensing, environmental determinants, climatic determinants, Canada

Introduction

Climate change has resulted in rising temperatures and ocean levels, increased climatic variability, and changes in the frequency and intensity of precipitation (1,2). Evidence of climate change started in Canada in the 1950s (3–6) and the average temperature has increased more than 1.5°C between 1950 and 2010—almost double the global average (7). The extent of this change has varied by region, with the most significant changes occurring in northern Canada and especially in the Arctic (8). The average humidity levels in Canada have also increased, with an average increase in precipitation of about 12% (8). These trends are likely to continue, with an increase in the intensity and frequency in extreme weather events such as heat waves, droughts, floods and forest fires (5,6,8–10). Urbanization, and its creation of heat islands, has contributed to these climate changes (11).

Climate has a direct impact on the movements of human populations and infectious disease vectors, such as ticks and mosquitoes, and their host populations (12,13). Increased temperature and climate variability are leading to an increase and geographic expansion of vector populations and the diseases that they transmit (1,7,11,14–22). The northern expansion of ticks, for example, has been demonstrated in numerous studies and has been associated with a steady increase in the number of human cases of Lyme disease (23–25). One study predicted that West Nile virus is likely to increase more than 17-fold by 2050 (26). With the northward expansion of the *Aedes albopictus* mosquito in the United States (US) (27,28), North America may be at risk for exotic mosquito-borne diseases (MBDs) such as dengue, Zika, yellow fever and chikungunya viruses. Other tick-borne diseases (TBDs) and MBDs are likely to increase or emerge in Canada as global warming occurs (26,27,29–31).

In light of the interplay between climate change and vector-borne diseases, it is increasingly important to be able to measure changes in temperature, precipitation and other variables related to habitat. Canada is a huge country, and current surveillance strategies are not designed to monitor the impact of climate change on the geographic spread of TBDs and MBDs. Earth observation tools are increasingly being used to increase our capacity to do so. Earth observation refers to the acquisition, processing, analysis, interpretation and dissemination of physical, chemical and biological information on land, oceans and the atmosphere by using satellite, airborne or *in situ* remote sensing sensors. Remote sensing technologies, which measure the properties of an object by means of electromagnetic waves, can be used in combination with many other terrestrial sensors, such as weather stations and balloon-probes (32).

This overview focuses on Earth observation images acquired by remote sensing satellites. Earth observation images and their derivatives provide data related to temperature, precipitation, humidity, forest, wetlands, agriculture, built environments and more. A number of studies have demonstrated the effectiveness of Earth observation images and their derivatives for risk assessment and mapping of TBDs and MBDs around the world. The Malaria Atlas Project (MAP) (33,34), the Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment (EPIDEMIA) (35) and the Mapping Malaria Risk in Africa (MARA) (36,37) are examples of monitoring programs based on the use of Earth observation images and their derivatives. In light of this, the use of Earth observation images to track TBDs and MBDs, and assess the geographic and climactic conditions for their spread, has been applied in Canada. The objectives of this overview are to describe how Earth observation image may inform risk assessment and mapping for the surveillance of TBD and MBD in Canada; summarize their potential benefits and limitations and identify the implications and next steps.

Earth observation images for risk assessment and mapping

Earth observation images are obviously not used to directly observe ticks and mosquitoes inside their habitats. Instead, Earth observation images are used to derive data on variables and indicators that serve to characterize the environmental and climatic determinants (ECD) that influence the presence and the development of ticks and mosquitoes. The ECD data is derived from Earth observation images through several processing and analyses methods, including geometric, radiometric and atmospheric corrections and image classification analyses. The resultant ECDs include surface temperature, air temperature, soil moisture, surface moisture, atmospheric water vapor, air humidity, amount of precipitation, topography, snow cover and thickness, soil type, vegetation type and density, vegetation indices, flooded areas, wetlands, water quality parameters (such as chlorophyll concentration, dissolved organic matter, suspended sediments, color, salinity), forests, urban and built-up areas and agricultural areas (33,38–40). Thus, many ECDs derived from Earth observation images are important determinants of TBDs and MBDs vectors survival and abundance. **Table 1** lists some of the most commonly used Earth observation satellites, their sensors, and their derivatives.

Mosquito-borne diseases

Environmental and climatic determinants of MBDs include both anthropogenic environments (such as urban, peri-urban and rural areas) and natural environments (such as forests and wetlands) (7,17,49–52). The ECDs include climatic and microclimatic factors that are known to affect the spread of mosquito-borne disease, such as temperature, humidity and precipitation (17,20,52–54). There are also specific ECDs for specific mosquito species. Some species, such as *Aedes albopictus* (that spreads dengue, chikungunya and Zika viruses) or *Culex pipiens* (that spreads West Nile virus), are highly adapted to urban environments. Other species, such as *Culiseta melanura* (that spreads Eastern equine encephalitis), are specific to natural wetlands and are found only in rural areas.

Tick-borne diseases

The ECDs of tick-borne diseases also vary by species. The Lyme disease vector, *Ixodes scapularis,* has evolved within temperate forest biomes (mixed hardwood) in North America, while the Powassan virus vector, *Ixodes cookei,* lives primarily in burrows and more rarely on vegetation. Historically, changes in the distribution of various types of habitat and host species have been associated with changes in the distribution and abundance of ticks (55). Tick-borne disease ECD include the type and density of forest cover and degree of forest fragmentation, as well as the prevailing temperature and humidity conditions in the forest habitats (12,13,17,56–63).

Risk assessment

The ECDs derived from Earth observation images have been used to assess the risks associated with different climate-related diseases (49,50,52,64–69). The possibility of human infection depends on a series of risks: the risk that the relevant vectors are present in the environment; the risk that those vectors are infected with a pathogen; the risk that human populations are exposed to those infected vectors; and the risk of disease transmission. The ECDs, derived from Earth observation image, combined with surveillance data, are used to assess, model and map these different risk components. Earth observation images and their derivatives can be used to map risk on a regular basis once the risk model based on those data has been developed and validated.

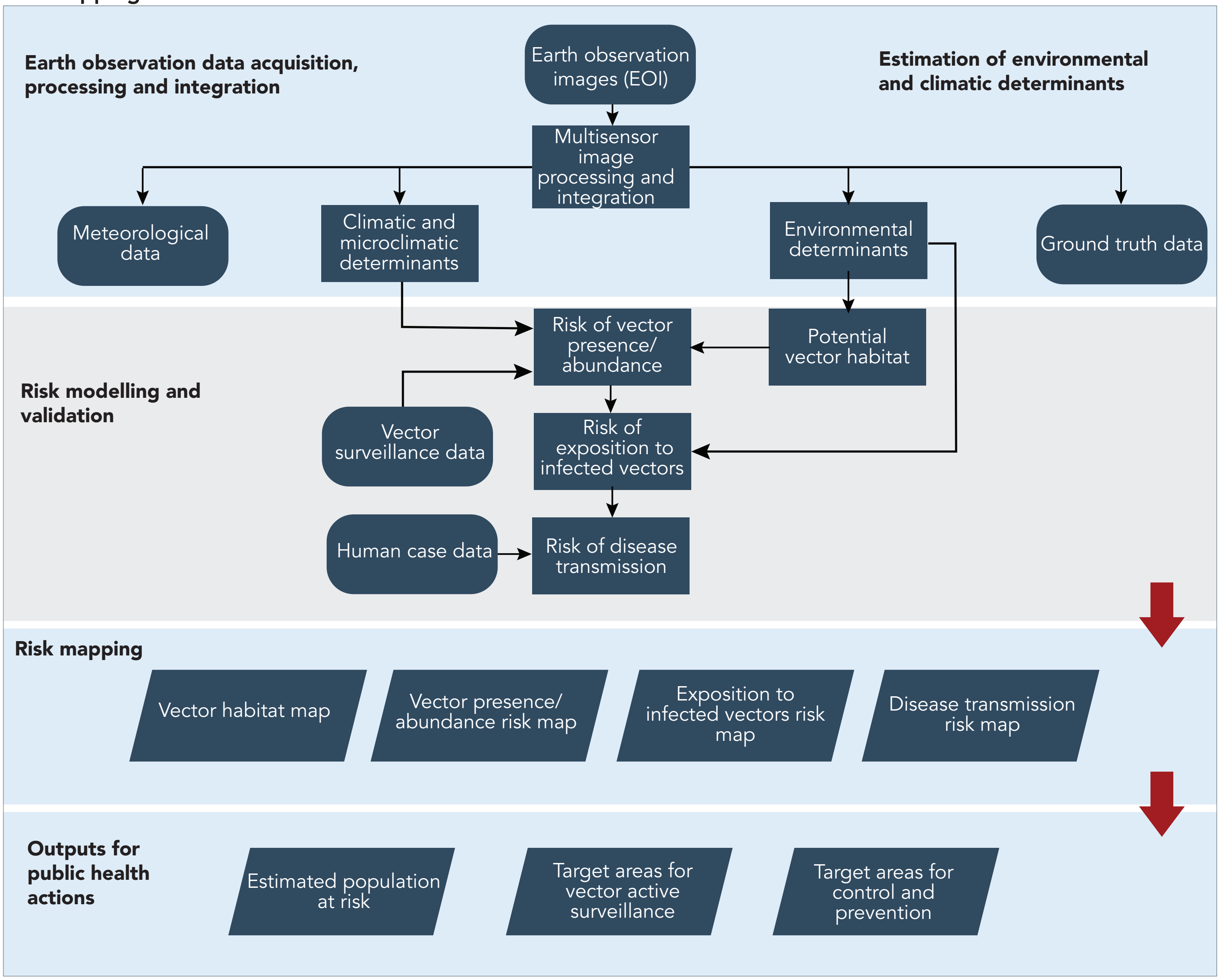
The most common use of Earth observation images for risk assessment and mapping is that of environmental risk associated with the presence or abundance of ticks and mosquitoes. The ECDs derived from Earth observation images can also be combined with human case data to directly assess and map the risk of disease transmission. **Figure 1** presents an example of an Earth observation-informed operational framework that can be used for climate-related infectious diseases risk assessment and mapping.

Table 1: In-operation open access Earth observation images and their derivative environmental and climatic determinants

Satellite name	Sensor	Spatial Res	Temp Res	Derivative environmental and climatic determinants										
				Land cover	Soil type	Veg type	Veg quantity	Snow cover depth	Water quality	Surface humidity	Surface Temp°	Air Temp°	Water vapour	Prec
Aqua	AIRS	2.3–41 km	0.5 day	-	-	-	-	-	-	-	Y	Y	-	-
DMSP	SSM/I	13–69km	1 day	-	-	-	-	Y	-	-	-	-	Y	Y
GCOM-W1	AMSR-2	3–62 km	1 day	-	-	-	-	Y	Y	-	-	-	Y	Y
GPM	DPR	5 km	1–2 hours	-	-	-	-	-	-	-	-	-	-	Y
GPM	GMI	4–32 km	1–2 hours	-	-	-	-	-	-	-	Y	-	Y	Y
Landsat-5	TM	30–120 m	16 days	Y	Y	Y	Y	Y	-	Y	Y	-	-	-
Landsat-7	ETM+	15–60 m	16 days	Y	Y	Y	Y	Y	-	Y	Y	-	-	-
Landsat-8	OLI	15–30 m	16 days	Y	Y	Y	Y	Y	-	-	-	-	-	-
Landsat-8	TIRS	100 m	8 days	-	-	-	-	-	-	-	Y	-	Y	-
MSG	SEVIRI	1–4.8 km	15 min	-	-	-	Y	-	-	Y	Y	-	Y	Y
NOAA 15-19	AVHRR/3	1.1 km	0.5 day	Y	-	-	Y	Y	-	Y	Y	-	Y	-
Sentinel-1	C-SAR	5–100 m	12 days	Y	-	Y	Y	Y	-	-	-	-	-	-
Sentinel-2	MSI	10–60 m	5 days	Y	Y	Y	Y	Y	-	-	-	-	-	-
Sentinel-3	OLCI	300 m	2 days	Y	-	-	Y	-	Y	-	-	-	-	-
Sentinel-3	SLSTR	500–1000 m	1–4 days	-	-	-	Y	Y	-	-	Y	-	-	-
SMAP	MWR	40 km	1.5 days	-	-	-	-	-	Y	Y	-	-	-	-
SNPP	ATMS	16–75 km	0.5 day	-	-	-	-	-	-	Y	-	Y	-	-
SNPP	VIIRS	375–750 m	6 min	-	-	-	Y	Y	-	Y	Y	-	Y	-
Terra	ASTER	15–90 m	5 days	Y	Y	-	Y	Y	-	-	Y	-	Y	-
Terra, Aqua	MODIS	250–1000 m	5 min	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-

Abbreviations: min, minutes; Prec, precipitation; Res, resolution; Temp, temperature; Veg, vegetation; Y, images acquired by the satellite/sensor system; -, not applicable
Satellite names: DMSP, Defense Meteorological Satellite Program; GCOM, Global Change Observation Mission; GPM, Global Precipitation Measurement Mission; MSG, Meteosat Second Generation; NOAA, National Oceanic and Atmospheric Administration; SMAP, Soil Moisture Active Passive; SNPP, Suomi National Polar-orbiting Partnership Satellite
Sensor names: AIRS, Atmospheric Infrared Sounder; AMSR, Advanced Microwave Scanning Radiometer; ASTER, Advanced Spaceborne Thermal Emission and Reflection radiometer; ATMS, Advanced Technology Microwave Sounder; AVHRR, Advanced Very High Resolution Radiometer; C-SAR, C-band Synthetic Aperture Radar; DPR, Dual-frequency Precipitation Radar; ETM+, Enhanced Thematic Mapper Plus; GMI, Global Precipitation Measurement (GPM) Microwave Imager; MODIS, Moderate Resolution Imaging Spectroradiometer; MSI, Multispectral Imager; MWR, Microwave (MW) radiometer; OLCI, Ocean and Land Colour Instrument; OLI ,Operational Land Imager; SEVIRI, Spinning Enhanced Visible and Infrared Imager; SLSTR, Sea and Land Surface Temperature Radiometer; SSM/I, Special Sensor Microwave Imager; TIRS, Thermal Infrared Sensor; TM, Thematic Mapper; VIIRS, Visible Infrared Imaging Radiometer Suite (41–48)

Figure 1: Earth observation-informed operational framework for climate-related infectious diseases risk assessment and mapping



Benefits and limitations

The use of Earth observation images and their derivatives to estimate ECDs and to map the risk of transmission of climate-related infectious diseases combines numerous advantages that cannot be matched by any other types of data (17,22,70,71). There are at least five potential benefits of using Earth observation images to inform public health risk assessment for vector-borne diseases in Canada.

First, Canada is a vast country that is not currently covered by field observation data use in traditional surveillance methods (e.g. trapping and analyzing density and type of mosquitoes or mapping out tick habitat by checking for ticks). These traditional surveillance data generally cover only a limited number of surveillance sites, which are unevenly distributed across provinces. In contrast, the Earth observation images cover continuous surfaces of the country, where each point of the observed territory is a "surveillance site". In addition, these images can cover large geographic areas such as Canada in a timeframe (minutes, hours and days, depending on the satellite used) that cannot be achieved by traditional surveillance methods.

Second, Canada has many remote regions that are difficult to access. These regions are covered by Earth observation images in the same way as the rest of the country. This offers the unique advantage of being able to continuously monitor even the more remote regions. This is particularly important in Canada, as some of these remote regions, such as the Arctic, are being disproportionately affected by climate change.

Third, in a related benefit, the use of Earth observation images would address the high cost of active surveillance over a large geographical area. Earth observation images acquired by multiple satellites are freely accessible via open data platforms or are accessible at low-cost. In Canada, there is a large amount of ready-to-use Earth observation image derivative data. These data are produced by federal departments, such as Agriculture and Agri-Food Canada, Natural Resources Canada and Environment and Climate Change Canada. They are freely available via the open government web site (https://open.canada.ca/en/open-data).

Fourth, active surveillance methods and protocols vary according to projects, years, programs and jurisdictions. This variability renders it difficult to make comparisons by time and place. In contrast, the Earth observation images are acquired on a standardised and regular basis. This enables comparisons of signal detections (e.g. abnormal situations and alerts) in a more efficient manner across the country.

Fifth, Earth observation satellites can be mobilized quickly to support real-time emergency operations in the event of major disasters that pose public health risks. For example, in the case of flooding, Earth observation images can be used to delineate and monitor risk areas where mosquito-control activities may be needed. The *International Charter on Space and Major Disasters* (72) was established to facilitate the mobilization of Earth observation satellites from various space agencies to support emergency operations related to major disasters. This charter was first activated for an infectious disease event during the Ebola outbreak in West Africa in 2014 (73). The benefits of using Earth observation images and their derivatives are summarized in **Table 2**.

Limitations

There are a number of limitations to consider with the use of Earth observation images and their derivatives.

First, Earth observation image derivatives were originally developed for other fields of application, including agriculture, forestry, and nature conservation and these data quality indicators were primarily intended to respond to the application objectives for which they were created. This means there is a lack of specific Earth observation image derivatives developed

Table 2: Advantages of using Earth observation images in the estimation of environmental and climatic determinants and risk mapping of climate-related infectious diseases

Advantage	Description
Accurate, regular measurements at different spatial and temporal resolutions	Compared with data acquired on the ground, the homogeneity and regularity of observations made using Earth observation images permit more accurate measurement of changes occurring over time, such as environmental and climatic changes. These measurements are made at different spatial and temporal resolutions which allow for the observation of phenomena (e.g. vector habitats, microclimatic conditions) and their changes according to a varied spectrum of measurement scales ranging from 0.31 m to over 75 km, and temporal observation frequencies ranging from 5 minutes to 16 days. This multi-scale observation capacity offered by Earth observation images is unique and makes it possible to estimate ECD and to map risk on local, regional and global scales according to the public health objectives.
High spatial density of observations, combined with coverage of vast territories, remote regions and areas difficult to access	The measurements made using Earth observation images are continuous data covering the entire geographic area covered by the sensor. ECDs can be estimated and low-risk or high-risk areas identified for any part of the territory. Earth observation image cover immense territories that cannot be sampled with ground data. Most Earth observation satellites can pick up images covering the entire planet, including remote regions and geographic areas difficult to access. This is very useful in supporting public health initiatives that target remote communities.
Recurrence of observations over a long period	Earth observation images have been acquired recurrently for nearly 40 years. The observation capacity for any given territory over long periods offers a great opportunity to study and predict the impact of climate change on the emergence and re-emergence of climate-related diseases.
Ready-to-use Earth observation image derivatives	Many ready-to-use products have been developed from Earth observation images to make these data accessible to a broader community of persons not expert in the processing and analysis of Earth observation images. These products relate to both environmental determinants and climatic determinants.
Low-cost access to vast amounts of data	There are over 1,700 Earth observation satellites in operation (74). Earth observation images from many of these satellites are accessible free of charge via open data platforms, as are the majority of Earth observation image derivatives. The majority of commercial Earth observation images involve data with very high spatial resolution (less than 2 m). Costs associated with these data are dropping quickly with the increase in Earth observation systems and the improvement of their performance.
Speed of mobilization of many satellites to support emergency operations	Under the *International Charter on Space and Major Disasters* (72), satellites and services can be rapidly mobilized by numerous space agencies to support the management of emergencies in major disaster zones. They offer the ability to quickly assess risks of epidemics in these zones in a context where the number of major disasters is rising with climate change. The Charter has been operational since the year 2000. It was activated to support responses related to the outbreak of the Ebola virus in West Africa in 2014 (73). This marked the first time the Charter was activated for the management of an infectious disease.

Abbreviation: ECD, environmental and climatic determinants for targeted infectious diseases like TBDs and MBDs. As a result, several data quality indicators (geographic coverage, spatial resolution, temporal resolution, temporal aggregation scale, update frequency, archiving period, composition of thematic classes, and data accuracy) of common Earth observation images and their derivatives do not meet data quality criteria needed for the estimation of ECDs associated to climate-related infectious diseases.

Second, the most used Earth observation images for the estimation of climatic and microclimatic determinants rarely have both high spatial and temporal resolution. For example, surface temperature and soil moisture can vary a good deal by place and over time. The Earth observation images that are used to calculate them do not allow for the combination of a high spatial resolution (less than 30 m) with a high temporal resolution (less than one day) (17,68,75); however, this combination is necessary to characterize the dynamics of the microclimatic conditions and vectors' microhabitats. Thus, these data do not always allow for control and prevention activities at a local scale (e.g. for a municipality).

Third, the use of Earth observation images and their derivatives to estimate ECDs on a fine scale and to produce risk maps over long periods and over large geographic areas generates a huge amount of data. The classic methods and technologies used for processing, analyzing, storage and management of such big data are currently limited.

These and other limitations associated with the use of Earth observation images and their derivatives are summarized in **Table 3**.

Discussion

Climate change is facilitating the emergence and re-emergence of tick-borne and mosquito-borne diseases in Canada. The use of ECDs derived from Earth observation images makes it possible to map the geographic expansion of these vectors and assess their disease risks. Currently, Earth observation images can cover all the urban, rural and remote regions of Canada in a standardized way on a regular basis at various spatial and

Table 3: Limitations associated with the use of Earth observation images and their derivatives

Limitation	Description
Coarse spatial resolution	The spatial resolution expresses the size of the smallest detail that can be observed in the image. A spatial resolution less than 30 m is generally recommended for mapping applications on a local scale. Earth observation images and their derivatives relating to climatic and microclimatic determinants have generally a coarse spatial resolution (more than 1000 m).
Low temporal resolution	Temporal resolution expresses the temporal frequency at which a satellite acquires Earth observation images for a same area. Bimonthly temporal resolution (16 days) is appropriate for Earth observation images used to estimate land cover environmental determinants. For Earth observation images that are used to estimate microclimatic determinants, a temporal resolution that can serve to establish daily averages would be more appropriate. However, commonly used free-access Earth observation images with a high spatial resolution (e.g. Landsat-8 images) do not have this temporal resolution.
Unknown or low accuracy	Climate change projections indicate temperature increases of 1°C to over 5°C in high latitudes, from the 1950s (76,77). An uncertainty below 1°C would be appropriate for Earth observation images and their derivatives related to temperature. Metadata of numerous Earth observational image derivatives do not indicate their accuracy, and the accuracy within any given Earth observation image derivatives can be highly variable and is generally not available.
Incomplete land cover classes composition	An Earth observation image derivative of environmental determinants must contain all the land cover classes representing environmental determinants of interest. However, the composition of land cover classes of a given Earth observation image derivative depends on its producer and the objectives of creating it. And, there is not a specifically-developed Earth observation image derivative to estimate all the ECDs of every climate-related infectious disease.
Inappropriate temporal aggregation scale	Temporal aggregation scale is the time step that is used to aggregate multi-temporal data. The aggregation scales that are mostly used for Earth observation image derivatives are daily, weekly, monthly and annual averages. The temporal aggregation scale to be used will depend on the vectors of the disease. The lifecycle of MBD vectors is very short (a few days to a few months), compared with that of TBD vectors (several years). A weekly scale is more appropriate in the first case and an annual scale in the second. However, for some ECDs, there are no Earth observation image derivatives with the target temporal aggregation scales (e.g. annual accumulation of surface degree-days, derived from land surface temperature images).
Long periods between updates	An annual update frequency is generally appropriate for Earth observation image derivatives used to estimate environmental determinants. However, several of these products are not updated annually.
Short archiving period	A relatively long archiving period—more than 15 or 30 years—may be necessary to study the evolution of infectious disease risks in the context of climate change. However, the archiving period of several Earth observation images and their derivatives is not long enough to study the impact of climate change on infectious diseases.
Incomplete geographic coverage	Risk assessment and risk mapping of infectious disease at borders often requires data covering several different administrative areas (e.g. Quebec/Ontario; Canada/United States).
Traditional methods and tools not adapted for massive Earth observation image data	An Earth observation image dataset covering a huge country like Canada, with a high spatial resolution, a high temporal resolution, frequent updates, and a long archiving period, will generate massive data for whose traditional methods and tools for Earth observation image data processing and management are not appropriate.

Abbreviations: ECD, environmental and climatic determinants; MBD, mosquito-borne diseases; TBD, tick-borne diseases temporal resolutions. However, the accuracy of Earth observation image derivatives is often not well known.

The accuracy of a risk mapping depends largely on the quality of the data used to model the risk and to produce the risk map. Improvements are being developed to derive better quality Earth observation image derivatives. For example, Earth observation images with different characteristics (including spatial resolution and spectral bands) have been combined via image fusion or downscaling methods to produce value-added Earth observation image derivatives that can meet the quality criteria required to estimate ECDs. For example, when land surface temperature (LST) images from Landsat-8's Thermal Infrared Sensor (100 m, 16 days) are combined with LST images from the Moderate Resolution Imaging Spectroradiometer (MODIS) (1000 m, 5 minutes), 8-day averages of LST images can be derived with a spatial resolution of 100 m (78). Using multisensor or multiproduct data combination, there are almost infinite possibilities for the estimation of ECDs and climate-related infectious diseases risk assessment and mapping in a context of rapid environmental change and increased climatic variability. Also, there is a need to apply artificial intelligence approaches to processing and analyzing the big data derived from combining data from multiple satellites. By doing so, it would be possible to create an Earth observation-informed operational framework for rapid risk assessment and mapping (EO-OFRAM) of climate-related infectious diseases. Such a platform would be fully automated and have an easy-to-use user interface that integrates monitoring data and other contextual data, and could be used to answer questions, visualize responses on maps, and produce status reports to inform public health action.

The authors are currently working with their academic and governmental partners to develop improved microclimatic indicators, vector microhabitat indicators and a data integration and fusion system. These innovative tools will improve the accuracy of ECDs estimation and support dynamic multi-scale risk assessment and risk mapping of climate-related infectious diseases via the EO-OFRAM. Under the *Innovative Solutions Canada Program*, the Public Health Agency of Canada has issued a challenge to industry regarding the processing and analysis of big data (79). Better processing and analysis of big data, including the application of innovative machine learning techniques (a subset of artificial intelligence), will enable the better use of the large volume of data produced by Earth observation images. The application of an artificial intelligence-enabled EO-OFRAM in public health depends on its effectiveness in assessing risk in different environments and at different levels of decision-making (local, provincial/territorial and national). The creation of an EO-OFRAM aims to equip and optimize monitoring as well as control and prevention activities at these three levels of governance. The major challenges of such an initiative are funding, the participation of public health from different levels of government and the development of common standards.

Conclusion

The risks associated with emerging climate-related infectious diseases are highly variable for different geographic regions over time. Earth observation images and their derivatives offer numerous advantages for characterizing this heterogeneity through the estimation of the environmental and climatic determinants and the mapping of climate-related infectious disease risks. With the development and application of improved approaches to process and analyze big data derived from Earth observation images, including machine learning, as well as the development of vector microhabitat and microclimatic indicators, the determinants derived from these Earth observation images offer some innovative tools to advance our risk modelling and mapping capacity to better support public health action again vector-borne diseases.

Authors' statement

SOK — Conceptualization, investigation, writing-original draft, review and editing
CB — Writing-original draft, review and editing
AL — Writing-original draft, review and editing
EER — Writing-original draft, review and editing
SB — Writing-original draft, review and editing

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Quebec's Multi-Party Observatory on Zoonoses and Adaptation to Climate Change

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Abstract

Climate change has been linked with the establishment and geographical expansion of zoonotic diseases, an example of which is the well-documented increase in human cases of Lyme disease in Quebec, Canada. As temperatures continue to increase in Quebec, it is anticipated that several zoonotic diseases will be affected. In response to the growing zoonotic issues facing public health authorities, Quebec's Multi-Party Observatory on Zoonoses and Adaptation to Climate Change (*Observatoire multipartite québécois sur les zoonoses et l'adaptation aux changements climatiques)* (the Observatory) was founded in 2015 as part of the Quebec government's Climate Change Action Plan (*Plan d'action 2013–2020 sur les changements climatiques*). The Observatory was designed to bring together agencies involved in formulating public policy and experts from the disciplines of human health, animal health and environmental sciences, in a manner similar to the innovative "One World, One Health" approach. The Observatory provides a platform for knowledge sharing and consensus building among representatives of public policy decision makers and scientists. Its main objectives are to anticipate and prioritize potential issues associated with zoonotic diseases in Quebec, in order to support applicable risk management and climate change adaptation. This article describes what the Observatory is, what it does and outlines its plans for the future.

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Introduction

According to the World Health Organization, climate change is the greatest single threat to human health in the 21st century (1). This threat has been linked to increases in chronic diseases, health problems related to extreme heat or floods, food shortages due to drought or flooding, smog- and pollen-related respiratory problems and a possible increase in conditions related to exposure to ultraviolet radiation (2). Climate change has also been shown to play a role in the establishment and geographic expansion of zoonotic diseases. Zoonotic diseases are defined as diseases or infections that are caused by viruses, bacteria, parasites, fungi or prions, and that can be transmitted between humans and animals (3). Zoonoses account for 60% of emerging infectious diseases and their significance in terms of global health is steadily increasing (4).

Climate change has been shown to result in warming temperatures and increasing precipitation, both of which influence the survival and spread of the zoonotic pathogens and/or the reproductive rate and geographic distribution of their vectors (5). Activities that extend the duration of transmission of zoonoses, as well as those that facilitate human exposure to the environment and thus to vectors and their associated pathogens, are also likely to be affected by climate change (5).

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In Quebec, average annual temperatures have increased between 1°C and 3°C since 1950 and are expected to increase by an additional 2°C to 4°C by 2050 (6). Monitoring of zoonoses in Quebec has shown an increase in human cases of zoonotic diseases, including Lyme disease (7). *Ixodes scapularis*, the primary tick vector of Lyme disease in North America, has gained between 35 and 55 km of geographic expansion each year in Canada, and this expansion has been clearly linked to climate change (8). An increase in the habitat of tick populations across Canada is likely to result in an increase in contact between humans and ticks (and tick-borne diseases) (9). Overall, the effects of climate change on zoonoses are poorly understood and challenging to predict, due to the complexity of their ecology and to the varying impacts of climate change upon them (10).

The aim of Quebec's Multi-Party Observatory on Zoonoses and Adaptation to Climate Change (*Observatoire multipartite québécois sur les zoonoses et l'adaptation aux changements climatiques*) (the Observatory) is to assess zoonotic diseases, to monitor trends and to educate and advise policy makers on how to address these infectious diseases, particularly in relation to how these zoonoses and their associated pathogens respond to climate change. The Observatory was founded in 2015 as a part of the government of Quebec's *2013–2020 Climate Change Action Plan*, which mandated the Ministry of Health and Social Services to develop the action plan's health-related components. The objective of this article is to identify what the Observatory is, what it does and to outline its plans for the future.

What the Observatory is

The Observatory is a collaboration of scientific experts and public policy makers across the province of Quebec (**Figure 1**). It has a unique organizational structure that follows the innovative "One World, One Health" approach (11). This approach is defined as the "collaborative efforts of multiple disciplines working locally, nationally and globally to achieve optimal health for people, animals and our environment" (12). The Observatory enables this collaboration through discussions and knowledge transfer among members specializing in three areas of expertise: human health; animal health; and environmental science. The Observatory structures and streamlines the networking of members through regular meetings and through a range of deliverables.

Figure 1: The Observatory's "One World, One Health" organizational structure

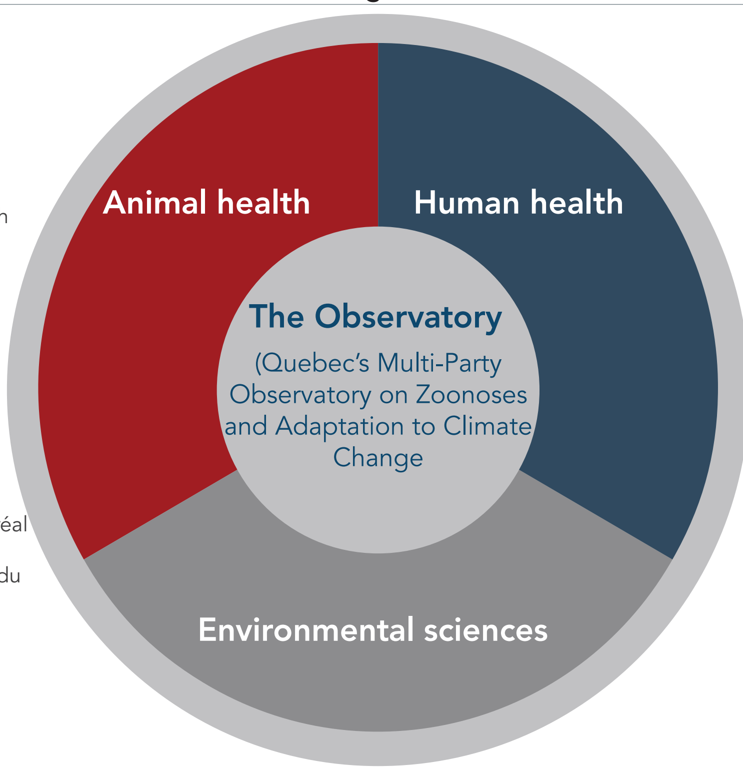
Scientific expertise

Experts:

- Veterinary public health
- Human public health
- Epidemiology
- Molecular biology—public health laboratory
- Preventive medicine
- Veterinary medicine
- Medical Microbiology and Infectious Diseases
- Environmental Health
- Entomology
- Climate change science

Organisations

- INSPQ
- GREZOSP – Université de Montréal
- Association des médecins microbiologistes infectiologues du Québec
- Ouranos
- Hôpital Sainte-Justine



Public Policy

Policy Makers:

- Ministère de la Santé et des Services sociaux (MSSS)
- Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ)
- Ministère de la Forêt, de la Faune et des Parcs (MFFP)
- Direction de santé publique régionale (DSPublique)
- Public Health Agency of Canada (PHAC)
- Canadian Food Inspection Agency (CFIA)

Abbreviations: INSPQ, Institut national de santé publique du Québec; GREZOSP, Groupe de recherche en épidémiologie des zoonoses et en santé publique
Legend: Diagram of the three areas of expertise at the core of Quebec's Multi-Party Observatory on Zoonoses and Adaptation to Climate Change, and the links among scientific experts and public policy decision makers

The Observatory is managed by the Biological Hazards and Workplace Health Directorate (*Direction des risques biologiques et de la santé au travail*) of Quebec's National Institute for Public Health [*Institut national de santé publique du Québec*, (INSPQ)]. The scientific coordination of the Observatory is provided via a partnership between the INSPQ and the Faculty of Veterinary Medicine of the University of Montreal, more specifically through the Zoonotic Epidemiology and Public Health Research Group [*Groupe de recherche en* épidémiologie *des zoonoses et en santé publique*; (GREZOSP)].

Most members participate solely on a voluntary basis. Two part-time coordinators, who provide operational support and who are responsible for the implementation of the Observatory's action plan, are remunerated. These coordinators also take part in a steering committee that validates their deliverables and operational decisions. There are also participants with relevant expertise in zoonoses and adaptation to climate change who contribute to, or are involved in, the Observatory's activities on an *ad hoc* basis.

What the Observatory does

In keeping with its mandate to create ongoing relationships among the scientific and public health authorities who are concerned by zoonoses and the adaptation of zoonoses to climate change in Quebec, and its aim to assess future and existing potential zoonotic infectious diseases, the Observatory:

1. Identifies, anticipates and prioritizes zoonotic and climate change related issues
2. Reports on the evolution of zoonoses, especially by monitoring of scientific literature, official reports, grey literature and current events, as well as information shared by and among members
3. Advises government decision makers regarding concrete actions that can be taken to manage zoonoses
4. Develops products to inform and increase the level of vigilance on zoonoses among members, as well as human health and animal health professionals

Prioritizing zoonotic issues

Shortly after the Observatory was established, its first initiative was to prioritize knowledge gaps limiting public health actions for the most important zoonoses (13). A report was created based primarily on expert opinion of the Observatory's members and collaborators. The report included a fact sheet on each of the principal zoonotic diseases prioritized by the Observatory, presented in a standardized data summary format; thus, making this information more easily accessible. Recommendations for public health authorities, regarding monitoring, prevention and control activities for the high priority zoonotic diseases, were included (13). These recommendations are used to assess provincial impacts of different zoonoses and to guide provincial public health authorities in their efforts to prioritize initiatives for adapting to climate change. The Observatory report was intended to identify future research areas for both researchers and funding agencies. An English version of this report will be available soon.

A second initiative, which began in 2018, involved a rigorous, transparent and systematic method of prioritization of zoonoses (14). This initiative was based on a multi-criteria decision analysis method (15). This method originated in operational field research and is used by different disciplines to rank options on the basis of both qualitative and quantitative criteria (15). Application of this decision analysis method led to a consensus list of 32 zoonoses, which were classified in order of priority according to their effects on public, animal and environmental health, their socio-economic impacts and their potential emergence or spread due to climate change. This analysis resulted in nine zoonotic diseases classified as "high priority". In descending order, these included West Nile virus infection, botulism, rabies, salmonellosis, listeriosis, *Escherichia coli* infection, hantavirus pulmonary syndrome, avian flu and Lyme disease (14). Hantavirus pulmonary syndrome and listeriosis fact sheets are currently being developed to complete the published report on prioritized zoonoses by the Observatory (13). An update of the prioritization is planned for every three years.

Monitoring trends

Another key function of the Observatory is regular scientific and tacit monitoring of the distribution of various zoonoses in Quebec. Scientific monitoring is done by monitoring of scientific literature, official reports, grey literature and current events. Tacit monitoring involves collecting relevant information on zoonoses-related issues from the Observatory members. These activities are done on an ongoing basis and the results are then summarized in the Observatory's annual newsletter.

Collecting and sharing information

Issues and needs regarding zoonotic diseases are identified through the prioritization process and during the Observatory's meetings, and are then communicated by members and collaborators to their respective networks and organizations. In addition, issues and needs are promoted through the Observatory's publications.

Educating and increasing awareness

To fulfill its knowledge transfer mandate, the Observatory regularly organizes webinars and conferences on zoonotic emerging issues, such as the arboviruses and enteric zoonoses emerging in Quebec in connection with climate change, or on broader themes such as vulnerabilities to zoonotic diseases in relation to climate change adaptation or ecosystemic approaches to health. The work of the Observatory is summarized in **Table 1**.

Table 1: The mandate, activities and actions of the Observatory in Quebec

Mandate	Activities	Actions	Examples
Identify and anticipate possible zoonotic disease and climate change issues	Prioritization exercise	Identifying the most significant zoonotic diseases in terms of effects on health, socio-economic impacts and potential emergence due to climate change Highlighting the knowledge gaps and related issues in relation to the prioritized zoonotic diseases	Prioritization publications: www.inspq.qc.ca/publications/2432 (French only) www.inspq.qc.ca/publications/2290 (French only)
Report on the evolution of zoonoses through monitoring	Scientific monitoring	Monitoring and providing summaries of scientific literature, official reports, grey literature and current events	Newsletter: www.inspq.qc.ca/zoonoses/observatoire/bulletin (French only)
	Tacit monitoring	Collecting tacit information and recent zoonoses-related issues from members during professional meetings	-
Communicate the identified issues and needs	Issue identification	Sharing meeting reports and highlighting monitoring and identified issues within their organizations	Meeting reports are relayed by the Observatory's members throughout their respective networks
	Circulation of publications	Drafting a communication plan to promote the Observatory's publications	Actions in the communication plan include participation in targeted conferences and promotion through the INSPQ and GREZOSP webpages
Develop knowledge-transfer products	Webinars	Organizing and promoting webinars on zoonotic emerging issues	Ten webinars on topics such as Lyme disease, Enteric zoonoses, Ebola in West Africa, monitoring of *Aedes albopictus* and modelling studies for mosquito-borne diseases
	Conferences	Organizing conferences for public health professionals	Three conferences as part of the Annual Public Health Days (e.g. 2018 presentation Regional Vulnerabilities to Zoonoses and Adaptation to Climate Change in Municipalities)

Abbreviations: INSPQ, Institut national de santé publique du Québec; GREZOPS, Groupe de recherche en épidémiologie des zoonoses et en santé publique

Discussion

With its innovative collaborative structure based on the "One World, One Health" approach, the Observatory enables ongoing assessment of the zoonotic situation in Quebec by including experts from human health, animal health and environmental science sectors. What makes this an innovative model for Canada is that the multi-disciplinary structure also includes the active engagement of agencies involved in formulating public policy.

The development and application of this new model has not been without its challenges. Given its wide range of expertise, there have been challenges to agreeing on definitions, achieving consensus on objectives and reaching common recommendations—especially when these agreements involve people from different disciplines who are new to working under the confines of a virtual multi-disciplinary structure. Thus, the initial projects have taken some time.

With both its strengths and challenges, important progress has already been made and the work of the Observatory will continue. The next major project will be the development of a zoonotic vulnerability assessment methodology. This project is consistent with the World Health Organization's *Vulnerability and Adaptation Assessment Guide*, which notes that vulnerability assessment is necessary to adapt to climate change (16). However, vulnerability assessment methodology has not yet been adapted to zoonotic issues in Quebec, and will be an important area of focus for the Observatory members.

In addition, an evaluation process has been initiated by Quebec's Ministry of Health and Social Services (*Ministère de la Santé et des Services sociaux*) to assess the Observatory's performance and implementation. The evaluation will determine how and to what extent the Observatory has fulfilled its mandate and contributed to both short- and medium-term impacts on members, collaborators and target audiences (scientific and academic experts, public health professionals and public policy decision makers). It will assess if collaboration has increased among Observatory's members and to what extent this has contributed to a better understanding of zoonotic issues and the impact of climate change. This evaluation will enable provincial government authorities to direct future actions as necessary.

Conclusion

The Observatory is an innovative response to the need to develop adaptive strategies to zoonotic infections that are increasing due to climate change. The Observatory enables collaboration and knowledge transfer among members specializing in human health, animal health and environmental science. By bringing together experts from these different fields and representatives of agencies involved in formulating public policy, the Observatory helps to prioritize, monitor and assess zoonotic issues related to adaptation to climate change. This knowledge transfer is pivotal to increasing Quebec's capacity to deal with the altering landscape of infectious diseases, particularly the alterations associated with climate change.

Authors' statement

GG — Conceptualization, writing—original draft, review and editing
AS — Conceptualization, writing—original draft, review and editing
JA — Review and editing
GB — Review and editing
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FEA — Review and editing
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