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A framework for adaptive surveillance of emerging tick-borne zoonoses

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ABSTRACT

Significant global ecological changes continue to drive emergence of tick-borne zoonoses around the world. This poses an important threat to both human and animal health, and highlights the need for surveillance systems that are capable of monitoring these complex diseases effectively across different stages of the emergence process. Our objective was to develop an evidence-based framework for surveillance of emerging tick-borne zoonoses. We conducted a realist review to understand the available approaches and major challenges associated with surveillance of emerging tick-borne zoonoses. Lyme disease, with a specific focus on emergence in Canada, was used as a case study to provide real-world context, since the process of disease emergence is ongoing in this country. We synthesize the results to propose a novel framework for adaptive surveillance of emerging tick-borne zoonoses. Goals for each phase of disease emergence are highlighted and approaches are suggested. The framework emphasizes the needs for surveillance systems to be inclusive, standardized, comprehensive and sustainable. We build upon a growing body of infectious disease literature that is advocating for reform to surveillance systems. Although our framework has been developed for tick-borne zoonoses, it is flexible and has the potential to be applied to a variety of other vector-borne and zoonotic diseases.

1. Introduction

We are currently experiencing an unprecedented increase in the (re-)emergence of infectious diseases. Examples of new diseases, diseases that previously existed but have moved into a new geographic area, evolved to infect a new host, or now cause more serious clinical disease, can be found across the globe [1]. Approximately 60% of these diseases are zoonotic, with the majority (~75%) having originated in wildlife [2]. Zoonotic disease emergence has been linked to major ecological changes facilitated by globalization and increased international travel and trade, climate change, habitat modifications, population growth and urbanization, agricultural intensification, and pathogen and vector evolution [3,4].

Tick-borne zoonoses (TBZ), which represent a subset of these emerging zoonoses, are complex systems involving a pathogen, vertebrate host(s), humans, and at least one tick vector. The environmental conditions in which each system exists strongly influence the presence or absence of infection and/or disease in susceptible hosts [5]. TBZ are highly sensitive to major global ecological changes and each component of the disease system can be impacted differently over time, making surveillance for and during disease emergence challenging [6–9].

A notable example of the emergence of a TBZ is Lyme disease (LD), which is the most common vector-borne disease in the temperate areas of the northern hemisphere [10]. LD has long been established in south and central Europe, northern Asia, and the northeastern United States [11–13]. Ongoing range expansion of the tick vector has contributed to changes in disease risk in these areas. Over the past two decades, the tick vector in eastern North America, *Ixodes scapularis*, along with the causative agent, *Borrelia burgdorferi* sensu stricto, has spread northward into Canada [14]. This process is anticipated to continue, in part due to climate change [15,16].

Given the current context of TBZ emergence, an evidence-based framework for surveillance that clearly documents the objectives for each stage of disease emergence, provides guidance on the utility of different surveillance approaches and allows for adaptation as the disease system changes would be of great value. Such a framework would help us target the already limited resources for surveillance efficiently and effectively in order to gather timely and important data for risk assessment of TBZ.

Our objective was to develop this evidence-based framework for

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adaptive surveillance of emerging TBZ. In order to develop the framework, we considered: (1) the main approaches used for TBZ surveillance, and (2) the major challenges associated with TBZ surveillance. We also deemed it necessary to examine a specific example of TBZ surveillance during the process of disease emergence which would allow us to further explore considerations (1) and (2) and potentially provide additional justification for our framework. Lyme disease, particularly in the Canadian context, provided a suitable example.

2. Methods

In order to develop the conceptual basis and operational requirements of an adaptive surveillance framework for emerging TBZ, we carried out a realist review of the available literature, with specific emphasis on LD and the Canadian context [17]. Realist reviews are designed to examine complex programs to understand what approach works, for whom and under what circumstances. It is not intended to provide a specific answer due to the context-specific nature of interventions that require holistic, multi-faceted approaches to assessment [17,18]. Two databases were chosen based on coverage: PubMed© and Web of Science®. Search results were restricted to publication dates from 1990 to present (December 2016) and English language only. Search terms were combined when appropriate using Boolean expressions. Titles and abstracts were reviewed (n = 339), and irrelevant articles were removed (n = 232). All remaining articles were reviewed in full and additional articles were added using snowballing (i.e., found when reviewing other articles) and review of grey literature (e.g., government documents, public health websites) (n = 40) (Fig. 1).

From the results of the realist review, we examined the available approaches, including the strengths and challenges. These results were used to develop the foundational aspects of our framework. Specific analysis of the Canadian context provided further data to refine and strengthen the framework into one that meets the needs of surveillance during a time of ongoing disease emergence.

3. Results

3.1. Illustrating the need for adaptive surveillance of emerging tick-borne zoonoses

3.1.1. Surveillance approaches for tick-borne zoonoses

The World Health Organization (WHO) [19] defines public health surveillance as “the continuous, systematic collection, analysis and interpretation of health-related data needed for the planning, implementation, and evaluation of public health practice.” Surveillance is applied to detect new public health threats, understand and monitor the epidemiology of disease, and assess the impact of public health interventions [19].

Passive surveillance involves the voluntary submission of health-related data from the public, health care providers and other members of society [20]. In the context of LD and other TBZ, a passive surveillance approach may involve the collection of tick samples from people or pets or submission of human case reports (e.g., notifiable disease reporting). Passive surveillance can be inexpensive and require less time and labour investment, when compared to other methods [21,22], but can be influenced by population density, as well as the level of effort placed into communication with and education of the public and medical communities [23–25]. A passive approach is well-suited to areas where there is limited information and can be used to establish a baseline of tick and pathogen distribution and monitor for deviations from this baseline [25,26]. Advanced analyses, such as with the application of remote sensing data, can also be conducted to understand the distribution and spread of the tick, risk factors for disease, and effectiveness of intervention methods [27–29].

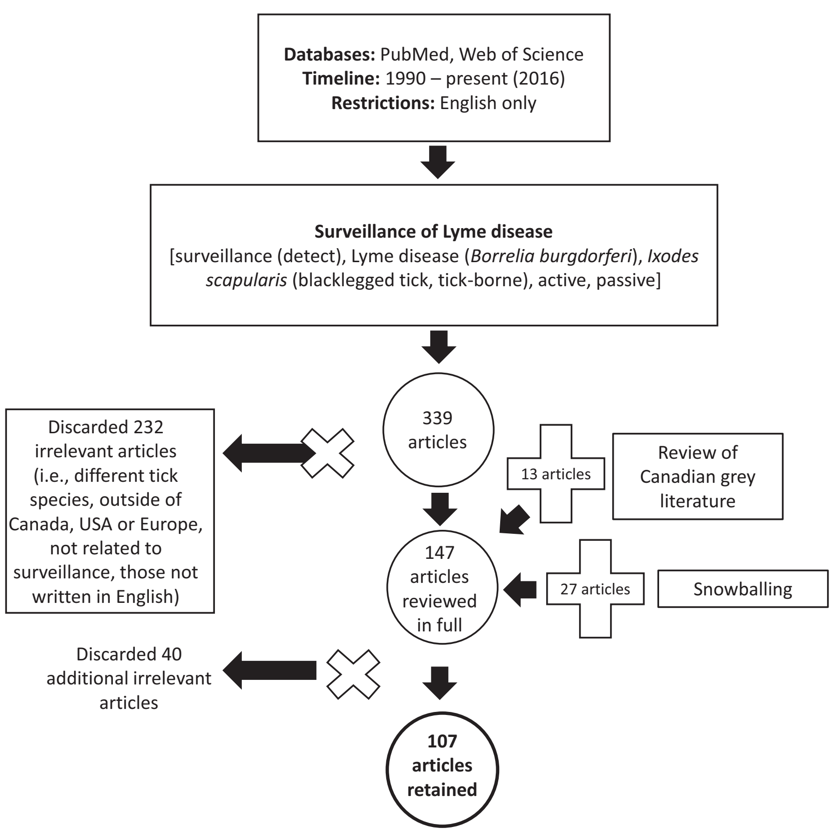

Fig. 1. A realist review was conducted to examine surveillance of tick-borne zoonoses. Lyme disease was used as a case study, with specific focus on the Canadian context.

Table 1
Alternative approaches for surveillance of *I. scapularis, B. burgdorferi,* or Lyme disease cases. Each approach has advantages and disadvantages, depending on the proposed application.

Approach	Advantages	Disadvantages	Selected references
Collection of dog serum samples. Serum from canine patients is evaluated for exposure to *B. burgdorferi*, either qualitatively (e.g., ELISA) or quantitatively (e.g., Quant C6). Typically, this research is conducted through participating veterinary clinics or veterinary laboratories.	Highly sensitive method; canine population has a much higher likelihood of encountering a tick (~6 times). May be a useful sentinel population for emerging risk and increased human exposure. Simple, quick, safe and relatively inexpensive collection. Patient data may be available to assess risk factors. Prolonged antibody production provides a wide time frame for detection.	Positive predictive value of test is influenced by the prevalence in the area (i.e., higher likelihood of false positives in low prevalence areas). May not have a central database for canine sera data. Clinic records may also be poor for follow-up. Selection bias may be introduced when only patients that visit a veterinary clinic are used. Contact with ticks, and exposure to pathogens is influenced by the routine application of tick prophylaxis. Travel history is not always available, so clinic location is used as proxy for exposure location.	[21,35-45]
Collection of ticks from hunter harvested deer. Researchers visit hunter check-in stations and examine the head and neck of deer carcasses for ticks. Tick samples are removed, identified and may be subject to pathogen testing.	Provides general insight into the tick species present in an area, and their potential distribution. Tick abundance on deer is positively correlated with the human incidence of Lyme disease. Tick infection prevalence can be examined for some pathogens.	Associated with low spatial specificity. Risk of false positive classification of an area may be high. Results can be influenced by deer density, and the researcher's search effort. Only feasible in areas that employ hunter check-in stations. Testing for *B. burgdorferi* can be less reliable. Deer are zooprophylactic and can clear *B. burgdorferi* from feeding ticks.	[46–54]
Mining of administrative claims data. Private medical insurance claims are reviewed for coding consistent with Lyme disease testing and/or treatment.	High sensitivity. Highlighted > 20% more cases than physician-reported cases. Provides some patient information for risk factor analysis.	Misclassification of cases probable as it can be difficult to know if the coding reflected the definitive diagnosis, or was only a differential diagnosis. Additionally, non-validated laboratories/testing procedures may be used, and these have been associated with high rates of false positivity. Unable to cross-reference with physician-reported cases as disease registry does not have individual identifiers. Resource and labor-intensive. Central database of all medical claims does not exist. Data mining must be completed for each company. Does not reflect cases presented at hospital. Only applicable in countries that have private medical insurance.	[55–61]
Mining of private testing laboratory data. Laboratories maintain information on the number of tests completed, the cost and the number of positive diagnoses.	Highly sensitive. Illustrates the degree of under-reporting that may exist. Data may be available for humans and dogs.	No clinical history present with the data. Unable to assess results in the context of presentation and clinical disease. Only applicable in places where private laboratory testing is available (e.g., USA). Data sharing not mandatory, so information only available from participating laboratories. Not all private laboratories use validated testing methods, making some results unreliable.	[62]
Exploration of Google Trends for Lyme disease. Similar to the *GoogleFlu* approach, analytics are used to assess the use of search terms "tick bite" and "Lyme disease". Data are explored geographically and temporally.	Positive correlation between search trends and the temporal and geographic incidence of human disease.	Over-interpretation of data (i.e., changes related to human factors rather than disease) Sampling bias due to non-representative sampling. Inaccurate model assumptions and approximations.	[63]
Use of sentinel medical practices. Switzerland formed a voluntary national network of 150 primary care practitioners that report specific information about tick bites and Lyme borreliosis.	Regular information collected on the incidence of tick bites, as well as clinical and demographic characteristics for Lyme borreliosis. Voluntary physician participation, which may lead to increased compliance with reporting.	Uneven geographic distribution of physicians, which may contribute to less generalizable information. Bias in reporting possible due to self-selection of physician participants.	[64]

Active surveillance involves coordinated efforts by public health officials to gather health-related data [20], which provides timely information that can be used to more accurately estimate the burden of disease. However, these methods can be labour-intensive and costly, which makes large-scale implementation difficult [21,22,30]. Collection of free-living ticks directly from the environment is one of the most common methods of active surveillance, as is the collection of ticks from small hosts (i.e., white-footed mice). Laboratory testing of these ticks for pathogens may follow. More detailed information on the presence and absence of the tick and pathogen, incidence of disease and risk factors can be gathered, which contribute to an enhanced understanding of disease and its ecology [31,32]. It is also possible to study multiple tick species and/or pathogens simultaneously [33,34].

In addition to the more common surveillance approaches described above, numerous other methods have been explored (Table 1). All approaches have benefits and drawbacks and can provide different information based on the context.

Despite these broad classifications of approaches, we advocate for a surveillance program that is not passive or active, but rather a combination of both, working synergistically. For example, passive tick surveillance can be employed broadly to see if there is evidence of emerging or changing risk. Active tick surveillance can then be employed in areas where risk may exist to gather more in-depth information. When risk is known, future data may be needed to understand the ecology of the disease system. At this time, active surveillance can be coupled with collection other ecological data (i.e., samples from hosts, climatic or habitat data). With careful assessment, we can design a surveillance framework that employs a variety of approaches over time in order to collect relevant data based on the stage of disease emergence.

3.1.2. Key surveillance challenges for tick-borne zoonoses

During the early stages of disease emergence, a general lack of awareness can impair surveillance efforts. Submission of ticks by the public relies on their awareness and engagement [25]. If physicians are not cognizant of the risk, there can be misdiagnosis and underreporting of cases [26,32,62]. Complacency of the medical profession may contribute to this issue, especially when the disease becomes endemic [23,65]. The opposite scenario can also occur. When the disease is heavily publicized, there may be an increased incidence, not due to a true change, but because of increased awareness, greater access to diagnostics, and more complete reporting [65,66].

Surveillance programs are planned and implemented at various geopolitical levels, based on arbitrary borders that do not apply to vectors [31]. This creates biases with surveillance data. Consider research conducted by Stefanoff and colleagues [67]. They compared the risk of LD between ecologically similar neighboring areas in Poland and the Czech Republic by collecting surveillance data from each country. The risk of LD was different for each administrative area, even after adjusting for potential confounding socio-economic factors, and could only be explained by differences in surveillance systems [67].

Many stakeholders are involved with TBZ surveillance. This includes public health officials, physicians, veterinarians, pathologists, epidemiologists, ecologists, entomologists, laboratory professionals, patients, and the public. LD surveillance efforts have frequently left important players out, leaving gaps in knowledge, misinformed programs, and repeated efforts. Even if all the needed stakeholders are present, there can be still be communication barriers [34,43,68].

Although our databases for TBZ are growing, the data collected are not routinely standardized. For example, when conducting tick dragging/flagging, both time and distance are used to standardize efforts, and the outcome of field sampling can be presence/absence of ticks, tick abundance, or tick density [32,69]. Additionally, tick dragging/flagging is conducted at different times of day and under different environmental conditions, all of which can impact the collection. From 1996 to 2007, four surveillance approaches were used to monitor human LD cases in Connecticut. Analysis of these data indicated large fluctuations in disease burden due to the different approaches, rather than a true change in disease risk [70]. Even with some standardization, little baseline data exist. Both presence and absence data are essential [31,71].

As with any program, finite resources exist for LD surveillance. This may limit the ability for surveillance to be conducted longitudinally, which impacts our ability to understand the nature of changing risk [31]. For example, in the United States, several state health departments passively collect case data from laboratories and physicians, and follow-up is conducted to gather patient information and verify the diagnosis. Funds are frequently exhausted, preventing reporting from being completed [30,72]. Cost-benefit analyses may be of value for surveillance interventions, so limited resources can be targeted to the most effective approach [69,73].

Integrating and interpreting the signals from different surveillance methods remains a challenge. Advanced analyses have been conducted to assess the signal from passive surveillance e.g. [27,74] and tools have been developed for interpreting active surveillance data, such as the screening test outlined by Ogden et al. [22]. Relationships between the incidence of human LD and ticks collected from dogs and white-tailed deer have been explored (Table 1). However, how these surveillance approaches fit together is still not well understood and future research is needed. Challenges also exist when new approaches are added, which occurs as disease emerges and needs change. For example, if a jurisdiction modifies its approach to conduct active tick surveillance and limit passive tick surveillance, the expertise and infrastructure required changes, as does the communication with and education of relevant stakeholders.

Finally, there are characteristics inherent to TBZ that makes surveillance inevitably challenging. Tick questing behaviour can be influenced by several factors, including time of day, weather and season, which can impact the number of ticks collected. Tick abundance can be variable across a small region, even when it is highly endemic [54,75]. There are still many ecological relationships that are not fully understood, especially in new areas of invasion [76]. Tick bites may not be detected, and there is a delay between transmission via a tick bite and the onset of symptoms [32]. Human disease can be difficult to diagnose, and the case definition needs to be appropriate to aid in diagnosis, yet provide flexibility in detecting atypical presentations [77,78]. Other tick-borne diseases can present similarly, contributing to greater difficulty with diagnosis [65].

Consideration of these challenges is imperative as we design our adaptive framework for surveillance of TBZ. If we continue to approach surveillance in the same way without addressing these challenges, we will continue to be limited in our ability to monitor for TBZ. Learning from past efforts will allow us to build a stronger system and thus improve our ability to effectively respond to TBZ.

3.1.3. Surveillance during the emergence of Lyme disease in Canada: a case study

LD is a recent public health issue in Canada. Prior to 1990, there was one known reproducing population of *I. scapularis* at Long Point, Ontario, with minimal spread of the vector outside of the area [79,80]. In the early 1990s, there was evidence that the distribution of *I. scapularis* was changing. By the mid-2000s, populations had been detected in Ontario along the north shores of Lake Erie, Lake Ontario, and the St. Lawrence River, and at numerous sites in Nova Scotia and southeastern Manitoba [14]. *Ixodes scapularis* continues to expand its range [81]. This had coincided with an increase in human LD, with incidence rising from 0.4 to 2.6 per 100,000 from 2009 to 2015 [82,83]. Of note, in British Columbia (western-most province), the situation is unique as the tick vector is *I. pacificus*. This tick has different ecological patterns compared to *I. scapularis*, including hosts preferences (i.e., lizards) and questing activity [84,85]. Ongoing research does not show the same rapid geographic expansion and elevation of disease risk seen in eastern and central Canada [84,85].

In 1991, public health officials and researchers met in Guelph, Ontario at the Canadian Consensus Conference on Lyme Disease [86]. This represented the first major step in addressing the potential risk of disease in the country. Previously, only Ontario, Manitoba and Nova Scotia had conducted some tick surveillance [87–89]. Consensus statements for epidemiology, epizootiology, clinical disease and laboratory diagnostics were developed, and rigorous criteria were established for surveillance [86]. This meeting was instrumental for starting the conversation on LD surveillance, and providing guidance to public health officials on an emerging issue. However, based on the consensus statement, there was not a clear action plan on how to move forward [86].

A multi-province passive tick surveillance program was subsequently launched by provincial and federal public health researchers in the early 1990s [90]. Canadians were encouraged to submit any ticks found on themselves or their pets to several research laboratories. Designated province-specific passive tick surveillance programs were initiated later in many jurisdictions [91–94]. Data collected via passive tick surveillance have contributed to a longstanding and invaluable database of tick submissions. Tick distribution in Canada has been mapped over time, and the data examined for significant spatial patterns to estimate risk and to determine specific areas for field sampling

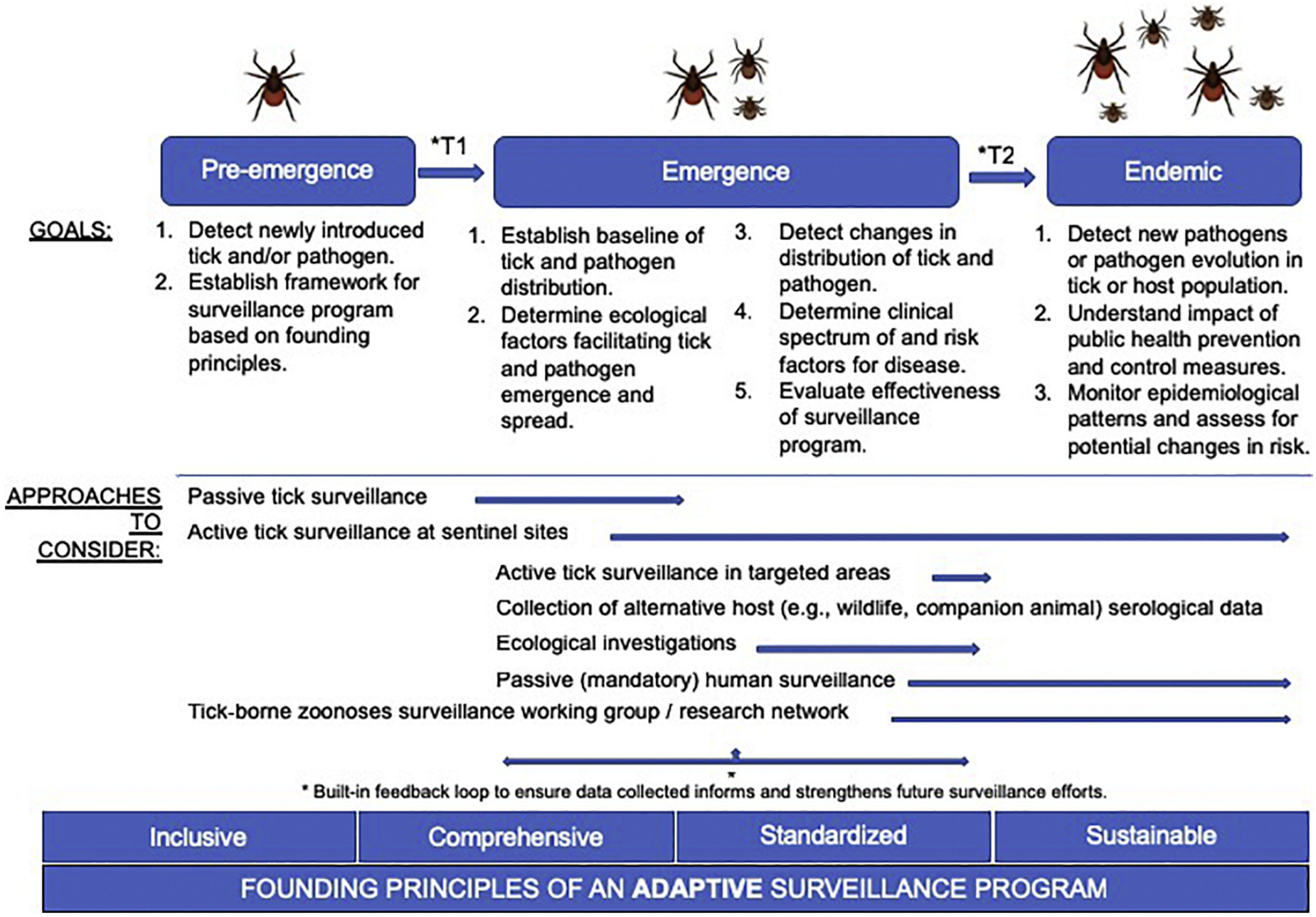

Fig. 2. A framework for adaptive surveillance of emerging tick-borne zoonoses can be employed by public health professionals. Goals for the disease context are provided along with surveillance approaches to consider. The framework is founded on four characteristics: inclusivity, comprehensiveness, standardization and sustainability.
(Tick image courtesy of the Centers for Disease Control and Prevention.)

[27,74]. Public health interventions, such as tick-bite prevention and education of the medical community, have also been targeted to the areas of greatest risk [83,95,96].

Active tick surveillance was subsequently initiated in most provinces. Currently, Ontario, Quebec, Manitoba, New Brunswick and Nova Scotia consistently conduct active tick surveillance, and this approach is applied in an area where there have been multiple tick samples submitted by passive surveillance [25,97–100]. Saskatchewan and Alberta have conducted active tick surveillance (i.e., drag sampling) more recently on an as needed basis [93,94].

To deal with the rapidly changing situation, health officials have moved away from the rigid classifications outlined in the Consensus Statement to the use of 'risk area' [99,101]. Determination of a 'risk area' generally requires less field sampling but has been shown to still provide an adequate assessment for a reproducing tick population [22]. The term 'risk area' however has not been applied consistently across the country [99,101]. This lack of standardization makes it difficult to understand and evaluate risk spatially and temporally in Canada. Communication with the public and between public health and other stakeholders would be enhanced with uniform terminology.

Surveillance approaches continue to evolve. In some highly endemic areas of Ontario and Nova Scotia, passive tick surveillance has been discontinued. Tick submissions provide minimal new information on *I. scapularis*, so they now only conduct targeted active tick surveillance to detect changes in the tick's range [98,102]. Evolution in a surveillance system is necessary in order to target approaches to those that will collect the most pertinent public health data based on the context. However, this must be done with caution as important data can also be lost. For example, if surveillance ceases in these areas, the ability to detect invasion of other tick species or changes in pathogen risk is severely limited. In this context, it may be valuable to have a small number of sites that are continually monitored for changes from the baseline.

Field sampling efforts have enhanced our understanding of the ecology of disease. Abiotic and biotic factors impact the tick and incorporating these variables into risk models and predictive mapping can enhance the applicability of these tools [28,32,76,103]. Active tick surveillance has also assisted with ongoing monitoring of the infection prevalence of *B. burgdorferi*, which is used to initiate prophylactic antibiotic treatment for humans [104].

In 2009, LD was declared a nationally notifiable disease in Canada, making it mandatory for all physicians to report any human case [105]. A voluntary LD enhanced surveillance system was also initiated and involves collecting more in-depth data on human cases.

Notable advances for strengthening the surveillance program for LD are ongoing. In 2014, the Public Health Agency of Canada created a 3-year Action Plan on Lyme disease, founded on the pillars of surveillance, prevention, and control [106]. Shortly thereafter, the Canadian Parliament passed a private member's bill, Bill C-442, which mandated a federal framework on LD including a national medical surveillance program [107,108].

By examining Canada's surveillance program throughout the process of emergence, we are provided with an example of how national and provincial public health were faced with a new threat and had to learn and adapt. We see how various surveillance approaches can be employed and what challenges may be encountered over time. From this case study, we synthesized lessons learned and applied them to further refine and strengthen our framework.

3.2. A framework for adaptive surveillance of emerging tick-borne zoonoses

Based on our realist review, we gained a broad understanding of the main approaches for TBZ surveillance and the current challenges that impact surveillance systems. Our case study of LD surveillance in Canada allowed us to examine TBZ surveillance over time in an area where emergence is ongoing, further highlighting how approaches can be applied and what challenges are encountered specifically during disease emergence. From both components of the review, we have highlighted the need for continued reform of surveillance systems and have applied these findings to propose “a framework for adaptive surveillance of emerging tick-borne zoonoses” (Fig. 2).

The framework is structured by stage of disease emergence, with goals outlined for each phase. Prior to disease emergence (i.e., “pre-emergence”), the priorities are to detect any newly introduced vector and/or pathogen, or an ecological change of relevance, and establish a surveillance program [7,109]. During disease emergence, we need to establish a baseline of vector, host and pathogen distribution and determine the ecological factors facilitating the transmission cycle [5]. As the process of emergence continues, we need to detect changes from the baseline distribution, understand the clinical spectrum of and risk factors for disease, and evaluate the effectiveness of the surveillance program [25,32]. If the disease becomes endemic, priorities may shift (in some cases) to detecting new pathogens or pathogen evolution in the vector or host population, understanding the impact of public health measures and monitoring epidemiological patterns for potential changes [1,34].

Approaches are proposed along a continuum and chosen based on an analysis of the strengths and weaknesses as well as potential synergism with other approaches. No specific timeline is provided, as the process of tick-borne disease emergence can be highly variable depending on the tick vector, pathogen, ecological factors, and public health interventions.

The foundational aspects of the framework are:

- ➢ Inclusive: All relevant stakeholders and levels of government with an active role in surveillance, prevention and control should be incorporated into planning and implementation of a surveillance program following a One Health approach [3,4,68,110]. Incorporating a participatory process with multiple stakeholders can determine knowledge gaps and prioritize efforts based on fiscal limitations [31,111]. It also helps address many challenges associated with non-uniform data collection and analyses and integration of approaches. Inclusivity does require communication, cooperation and active participation from a broad range of stakeholders, as well as time and resources, all of which may present a challenge in certain environments.
- ➢ Comprehensive: Surveillance programs must go beyond simply tracking human disease cases and include efforts to understand the distribution of the tick and pathogen in nature [31,112]. This includes examination of tick abundance and pathogen infection prevalence at relevant spatial and temporal scales. With a comprehensive program, the ability to analyze different datasets and explore opportunities for integration and synergy can be enhanced. This will ultimately drive the advancement of more efficient and effective surveillance program.
- ➢ Standardized: For data to be shared between relevant stakeholders and across administrative borders, standardized ways of measuring and recording surveillance information need to be used [67]. This does not imply that previously collected data are no longer useful. It simply emphasizes that greater utility will be gained from data if we can move towards standardized protocols (e.g., case definitions, measures of tick abundance, pathogen testing), and a centralized database for data deposition, acquisition, and subsequent analyses. Many of the previously described challenges relate to non-uniform data collection and access, which greatly impedes any future data analysis and knowledge translation to public health stakeholders. Great strides can be made if all stakeholders use a common language.
- ➢ Sustainable: Indeed, tick-borne disease surveillance, just like many other public health programs, is constantly faced with resource limitations (e.g., financial, human resources, time). TBZ emergence can be a long-term process, with a complex ecology, thus demanding more resources. However, if only short-term surveillance initiatives are explored, we will only have a snapshot of risk. Surveillance programs that are designed with a longer-term vision enhance our ability to assess risk, understand the changing nature of the risk and predict future risk [65].

These foundational elements are intricately related, and each provides strength to the other.

4. Discussion

There is a wealth of literature on infectious disease surveillance, particularly in regard to evaluation of current surveillance systems for specific diseases e.g., [113,114]. With an accelerated rate of disease emergence driven by global ecological changes [2–4], the body of literature proposing reform to surveillance systems to respond to future risks is growing. In reference to vector-borne zoonoses, there is a strong emphasis on integrated surveillance that applies a One Health approach to collect data from across the disease system (i.e., vectors, hosts – human and non-human) [31,115–117]. The need for context-specific design of surveillance systems has also been proposed in reference to wildlife disease epidemics and subsequently vector-borne disease [110,118,119]. We have built upon these concepts in our framework, which explicitly describes an “adaptive” approach to surveillance for emerging tick-borne zoonoses in order address the conceptual and logistical challenges of generating appropriate and useful surveillance data across all phases of emergence from pre-emergence to endemicity.

The framework outlines what we believe is an ‘ideal’ design of a surveillance system. We do not believe it is unachievable, but acknowledge that implementation will take time, effort and resources, and may be subject to many of the geographic, political and financial challenges previously discussed. A stronger surveillance system can nonetheless be built with this framework in mind, in full or in part, over time. If resources are severely limited, it is valuable to focus on the goals for the phase of disease emergence and assess the strengths and weaknesses of the available surveillance approaches to determine the most suitable way forward. Continual assessment and adaption can help ensure that the resources are being put towards efficient and effective approaches.

To apply the Framework, previously collected data can be used to determine the phase of disease emergence for the TBZ of concern. Specific surveillance activities are subsequently suggested for each phase, but approaches do not necessarily need to be limited to these activities. They should however be appropriate for achieving the goals of that phase.

Although this framework was developed based on Lyme disease, it is easily applicable to other contexts, including other pathogens and other tick vectors. For example, if we again consider *I. scapularis*, this tick is the vector for numerous other pathogens of public health significance, including *Anaplasma phagocytophilum*, *Babesia microti*, and *B. miyamotoi* [120–122]. Although the infection prevalence of these agents in tick populations is currently low in Canada, awareness of risk and subsequent minor adjustments to the surveillance system, such as comprehensive laboratory testing of ticks in conjunction with ongoing tick surveillance initiatives will allow for early recognition of potential changes [25,123]. If we consider other tick vectors, passive tick surveillance and targeted field sampling can be conducted with these risks in mind, and data collection can contribute to ongoing monitoring of risk for other tick species and tick-borne diseases [75,123]. For example, in Ontario, Canada, concern exists for range expansion of the lone star tick (*Amblyomma americanum*). Public health officials are aware of this risk and in the process of adjusting the current surveillance system to monitor for potential changes that may indicate population establishment of this tick species [124].

5. Conclusion

The proposed framework provides guiding principles for planning surveillance for early detection of tick-borne zoonoses that pose an imminent threat. Perhaps more importantly, it identifies objectives and associated surveillance methods for different phases of disease emergence, providing a planning tool for transitioning from one type of surveillance to another as a region moves from pre-emergence through to endemicity. This transition can be difficult to orchestrate but if done effectively it provides the opportunity to reduce the overall cost of surveillance by optimally allocating public resources over time. Many of these challenges and opportunities are not unique to tick-borne zoonoses, and many features of the proposed framework may be usefully applied to optimize surveillance in the context of other types of emerging disease.

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Conflict of interest

The authors have no potential conflict of interest to disclose.

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