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Canadian wildlife health surveillance—patterns, challenges and opportunities identified by a scoping review

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Abstract

The protection and promotion of healthy wildlife populations is emerging as a shared goal among stakeholders in the face of unprecedented environmental threats. Accordingly, there are growing demands for the generation of actionable wildlife health information. Wildlife health surveillance is a connected system of knowledge that generates data on a range of factors that influence health. Canada recently approved the Pan-Canadian Approach to Wildlife Health that describes challenges facing wildlife health programs and provides a path forward for modernizing our approach. This scoping review was undertaken to describe the range of peer-reviewed Canadian wildlife health surveillance literature within the context of the challenges facing wildlife health programs and to provide a quantitative synthesis of evidence to establish baselines, identify gaps, and inform areas for growth. This review describes patterns related to species, location, authorship/funding, objectives, and methodology. Five areas are identified that have the potential to propel the field of wildlife health: representativeness, expanded/diversified collaboration, community engagement, harmonization, and a shift to a solutions-focused and One Health mindset. This scoping review provides a synopsis of 10 years of Canadian wildlife health surveillance, challenges us to envision the future of successful wildlife health surveillance, and provides a benchmark from which we can measure change.

Key words: Canada, Canadian wildlife, scoping review, wildlife health, wildlife health monitoring and surveillance, wildlife disease monitoring and surveillance, wildlife health and disease research

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Introduction

Wildlife populations provide economic, cultural, and ecological services, the collective value of which is worth billions of dollars to the Canadian economy (Federal, Provincial, and Territorial Governments of Canada 2018). These populations are critically important for food security and for the physical and mental health of geographically dispersed communities that rely on wildlife for sustenance and livelihood (Environment and Climate Change Canada 2019). Recognition of the benefits associated with healthy wildlife populations is accompanied by growing concerns about wildlife as sources of emerging infectious diseases. Certainly, the ongoing COVID-19 pandemic has cast a spotlight on the human–animal disease interface and has also demonstrated the urgency with which we must consider the human dimensions of wildlife health in how we respond to and communicate about wildlife disease (Leong and Decker 2020). Unbalanced media coverage focused on the threat wildlife pose to human health, rather than the benefits associated with healthy populations, increases risk perceptions (real or perceived) associated with wildlife disease and may decrease public support for conservation (Buttke et al. 2015; Decker et al. 2016). Such collateral impacts also undermine support for responsible stewardship of natural resources (e.g., wildlife populations) as a critical tool for preventing future zoonotic disease transmission at the wildlife–human interface. The concept of wildlife health, as opposed to viewing wildlife only as sources of disease, is therefore increasingly relevant to wildlife managers (Decker et al. 2016), and the protection and promotion of sustainable, healthy wildlife populations has emerged as a guiding and shared priority among stakeholders and decision-makers (Decker et al. 2016; Federal, Provincial, and Territorial Governments of Canada 2018; USGS National Wildlife Health Center 2019). Accordingly, there are growing demands for the generation of actionable wildlife health information (Stephen et al. 2018).

This information is typically generated by a range of sources and through a combination of surveillance programs, surveys, research projects, and consultations depending on available resources, capacities, expertise, funding, and research priorities (Stephen et al. 2018). While all these mechanisms of knowledge acquisition may support decisions affecting wildlife, monitoring and surveillance activities are in theory distinguished through a requirement for "continuous or repeated measurement" and surveillance further entails the generation of data that are "linked with action to mitigate risk" (Hoinville et al. 2013).

Wildlife health has historically been considered in the context of presence/absence of pathogens and (or) toxins; however, perspectives have evolved to acknowledge that there are a wide range of social and ecological drivers of health. Recurring concepts in the literature describe wildlife health as a multidisciplinary concept that applies to individuals and (or) populations and is not defined by the absence of disease but assessed in the context of capacity to cope with change while maintaining ecosystem and societal expectations (Hanisch et al. 2012; Patyk et al. 2015). In practice, health outcomes are dependent on the interactions of multiple and diverse contributing factors (Stephen 2014; Wittrock et al. 2019). Thus, the scope of activities considered under the umbrella of wildlife health surveillance extends beyond those that collect data on physiologic state and presence/absence of pathogens and (or) toxins to include those which generate data on a broad range of metrics (e.g., behaviour, habitat/range use, demography, population dynamics, body condition).

In Canada, responsibility for the management of wildlife health is shared between federal, provincial, territorial, and Indigenous governments. However, many nongovernmental organizations also have an important role in these efforts. For example, the Canadian Wildlife Health Cooperative (CWHC) functions as a centralized network of wildlife health expertise and works to bridge jurisdictional gaps where wildlife health issues fall across departments and levels of government (Canadian Wildlife Health Cooperative 2021). As one of its core activities, the CWHC supports a national wildlife health surveillance program operated through partnerships with Canada's five veterinary colleges and the British Columbia Animal Health Centre (Canadian Wildlife Health Cooperative 2021).

To adapt and meet the unprecedented challenges facing wildlife populations, the CWHC and a network of Canadian wildlife agencies and professionals came together to establish a modernized approach to wildlife health: A Pan-Canadian Approach to Wildlife Health (PCAWH). Approved in June 2018, the PCAWH describes a number of challenges facing wildlife health programs in Canada including: ability to provide assurances of wildlife health across a wide range of species and vast geography, building partnerships that cross boundaries and affiliations, meeting expectations for proactive recommendations to help navigate rapidly changing environmental conditions, and ensuring an adaptable but coordinated approach (Federal, Provincial, and Territorial Governments of Canada 2018).

The PCAWH framework outlines a path forward guided by four key areas of focus: health intelligence, stewardship, innovation, and governance (Federal, Provincial, and Territorial Governments of Canada 2018). Information gathering was identified as a crucial component of this comprehensive framework for national wildlife health programming. Wildlife health surveillance is also included as a core component of Canada's National Biodiversity Targets, with the number of peer-reviewed reports used as an indicator of progress towards these goals (Environment and Climate Change Canada 2019).

Wildlife health surveillance data may be accessible through the peer-reviewed published literature, available within the grey literature, contained within archives, or exist only as institutional/expert knowledge. Historically these data have not been collated within a centralized repository and methods for connecting and synthesizing these data remains a critical gap. The published literature represents a body of work that has undergone the rigorous process of peer-review, has standardized search methods, and exists in a relatively standard format, including the detailing of methodology. The scope of this review has therefore been limited to the inclusion of published peer-reviewed literature. Undoubtedly a review of wildlife health surveillance in the grey literature would be an important area for future study and present a valuable comparison around the nature and scope of wildlife health surveillance that results in peer-review publication versus that which exists within the grey literature.

A scoping review was undertaken to: (*i*) describe the range of peer-reviewed Canadian wildlife health surveillance literature within the context of the wider challenges facing wildlife health programs as identified in the PCAWH document, and (*ii*) provide a quantitative synthesis of evidence to establish a baseline, identify gaps, and inform areas for growth and improvement. We focused on identifying patterns related to species and geography, authorship and funding affiliation, objectives, and methodology,

Materials and methods

The scoping review framework proposed by Arksey and O'Malley (2005) and the work of Levac et al. (2010) were consulted prior to conducting this scoping review. The PRISMA extension for scoping reviews checklist was consulted for reporting guidance (Tricco et al. 2018).

Search strategy

A scoping review was conducted in the following databases: Pubmed, Web of Science, and CAB Direct. Our search protocol was developed *a priori* in collaboration with University of Guelph library services; registration of the search strategy was not completed. The search was conducted on 4 January 2018 with no date or language restrictions and all fields were queried for search terms. **Table 1** outlines the key words used in the search strategy.

Screening

All citations identified through the key word search were imported into the Mendeley reference management software (version 1.19.4), duplicates were removed, and all remaining citations were exported into Microsoft Excel (version 2002). Following consultation with all authors, the date of the review was restricted to manuscripts published between 2007 and 2017 inclusive, and manuscripts focused on invertebrates were excluded to accommodate time and resource limitations. The title and abstract of all entries were screened for inclusion/exclusion.

In line with recent literature and expert opinion, the authors adopt an inclusive definition of wildlife health surveillance that encompasses a range of data that are relevant for understanding wildlife health at the individual and population level, rather than simply surveillance of individual health status (Stephen 2014; Wittrock et al. 2019). Therefore, studies were considered relevant if qualitative

Table 1. Search terms used to conduct a scoping review of published wildlife health surveillance in Canada.

Concept	Key words
Wildlife	"wildlife" OR "wild animal*" OR "animal* wild" OR "nondomestic animal*" OR "non-domestic animal*" OR "animal non domestic"
Surveillance	"surveillance" OR "sentinel surveillance" OR "syndromic surveillance" OR "population surveillance" OR "health surveillance" OR "public health surveillance" OR "disease surveillance" OR "surveillance system*" OR "monitoring" OR "survey*"
Canada	"Canada" OR "Canadian" OR "Ontario" OR "Alberta" OR "British Columbia" OR "Saskatchewan" OR "Manitoba" OR "Quebec" OR "Québec" OR "Prince Edward Island" OR "Nova Scotia" OR "Newfoundland" OR "Yukon" OR "Nunavut" OR "Northwest Territories" OR "New Brunswick"

or quantitative data collected about Canadian free-ranging wildlife (nondomesticated vertebrates) species were presented; a critical analysis of study quality was not performed. Studies were excluded if wildlife data were not presented (e.g., environmental sampling without reference to wildlife), data were collected from wildlife outside of Canada, data were collected from captive wildlife, or if the manuscript was a review article, described a laboratory/challenge study, or the objectives were focused on the development/validation of a methodology or diagnostic test. When inclusion/exclusion could not be determined based on title and abstract, the item was moved forward for full-text screening. The initial title and abstract screen was completed by two reviewers (JG, MR). The first 20 items were screened independently by both reviewers, results were compared, and all discrepancies were resolved through discussion. The inclusion/exclusion criteria were then updated for clarity and precision. An additional 20 items were screened independently and compared between the reviewers to ensure consistency and all remaining entries were divided between the two reviewers to complete the initial (title and abstract) screening step. A copy of each manuscript that screened in was accessed, where possible, for all remaining citations. A full-text review was completed following the same inclusion/exclusion criteria to confirm relevance and identify data elements to extract.

Data charting and analysis

Data extraction was performed in Excel. Pertinent manuscript characteristics were determined *a priori*, and data categorizations were tested on 20 articles by two independent reviewers (JG, DB). The reviewers met to resolve discrepancies in data extraction and categorization; consultation and consensus with a third reviewer (EJP) were used to update the data extraction form for clarity and precision. The articles were divided, and data extraction was performed by two reviewers (JG, DB). The form consisted of 31 characteristics and was designed to extract data to describe species, location, author and funding affiliation, study objectives, and methodology. The species sampled were categorized according to vertebrate class (i.e., amphibian, bird, fish, mammal, and reptile) and species category according to taxonomic order and (or) family as deemed informative by the authors (Supplementary Table SII). Location of sampling was categorized according to provincial/territorial boundaries and grouped as 6 regions based on comparable ecosystems (i.e., British Columbia, Prairies (provinces of Alberta, Saskatchewan, Manitoba), Ontario, Quebec, Atlantic (provinces of New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador), and North (Yukon, Northwest Territories, and Nunavut)). Whether the study area was described as an urban, rural, or a combination of the two environments was also recorded. Author and funding affiliation was categorized according to broad sector (e.g., academic, federal government) and institution (e.g., specific university, organization, or ministry). Objectives were categorized according to theme (e.g., population/fatality count, describe/understand behavior), whether they were framed within the

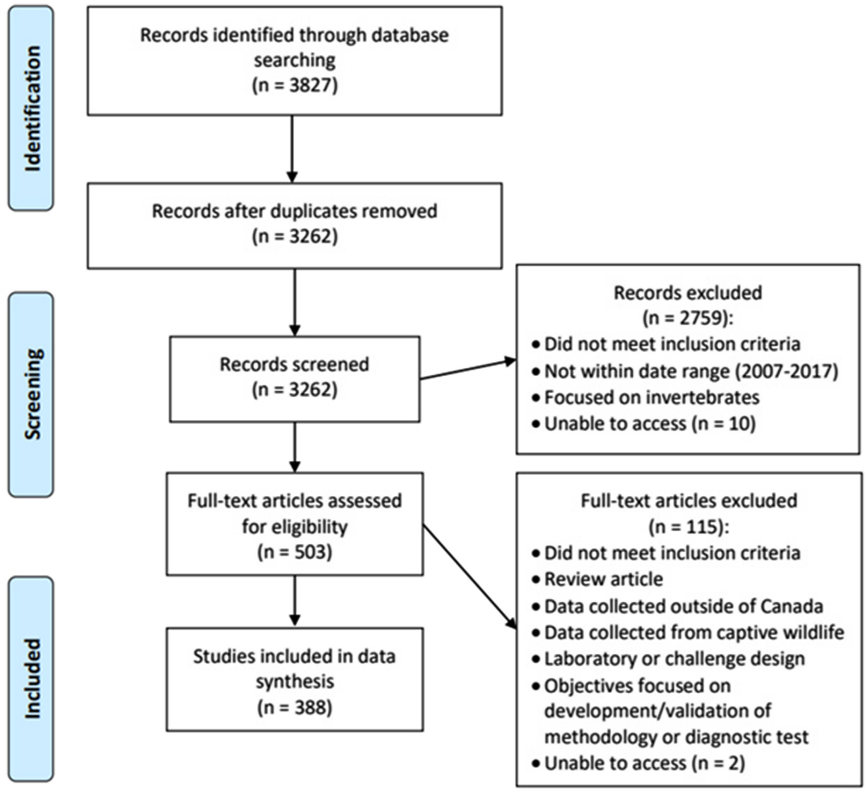

Fig. 1. PRISMA flow diagram depicting the results of the scoping review search strategy and manuscript selection process (Moher et al. 2009).

context of relevance for management/policy, and more generally by application (i.e., the sector(s) to which study significance was framed: wildlife health, environmental health, public health, and domestic animal health). Methodological data extracted included: length of study, surveillance method, data collector, and sampling method. More complete descriptions of each characteristic and detailed information regarding species categorizations can be found in the supporting material (**Supplementary Tables SI, SII**). Data extraction was performed based solely on information provided within the manuscript except for the categorization of author affiliation and funding agency; in cases where the reviewers were unfamiliar with a listed organization/institution, an online search of the name was performed to verify that the correct affiliation categorization was assigned. Descriptive analyses (proportions and percentages) were performed in Excel. Tables and graphical representations were developed in Excel to convey patterns.

Results

Search results

The literature search yielded 3827 citations (PubMed: 995 articles, Web of Science: 727, CAB Direct: 2105) of which 503 were retained for full manuscript review. Of these, 388 met inclusion criteria and were included in data extraction (**Fig. 1**). A list of included manuscripts is available upon request.

Data overview

Overall summary characteristics for the 388 manuscripts included in the scoping review can be found in the supporting material (Supplementary Table SI). Data were not available for all variables; therefore, the denominators vary and are presented for clarity. The following results describe pertinent summary characteristics.

Species

The surveillance literature was focused on birds and mammals regardless of region (Figs. 2, and 3). The most frequently studied species categories included terrestrial carnivores (75/388; 19%), seabirds (74/388; 19%), ungulates (72/388; 19%), and waterfowl (51/388; 13%) (Fig. 3). The majority of reptile and amphibian literature focused on turtles (12/14; 86%) and frogs and toads (14/16; 88%), respectively (Fig. 3). Few studies sampled across taxonomic group (multiple vertebrate classes 19/388, 5%; multiple species categories 71/388, 18%) (Fig. 4).

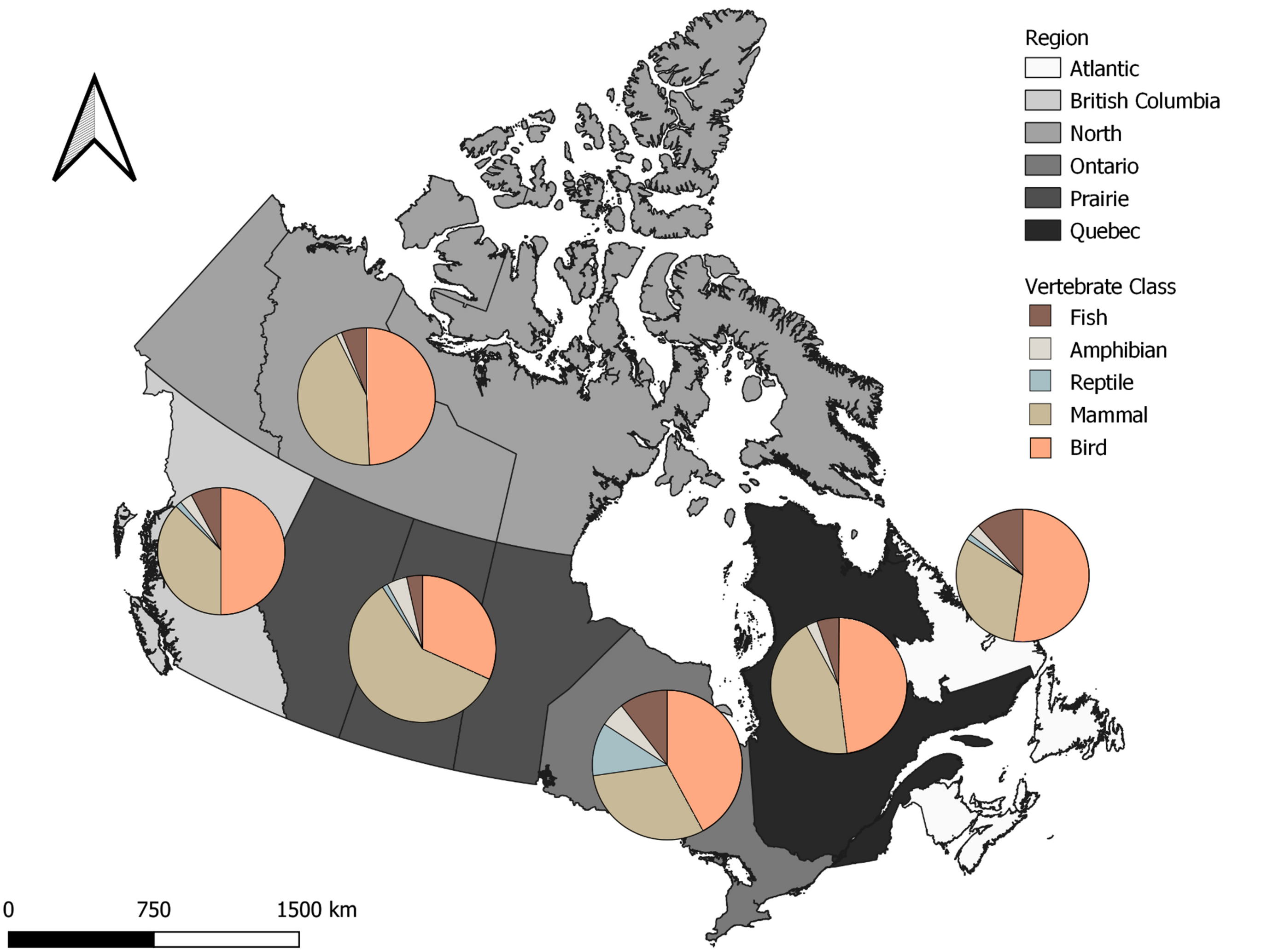

Fig. 2. The geographic distribution and taxonomic representation of 388 manuscripts presenting Canadian wildlife health surveillance data. The area of each pie chart is proportional to the number of manuscripts from that region.

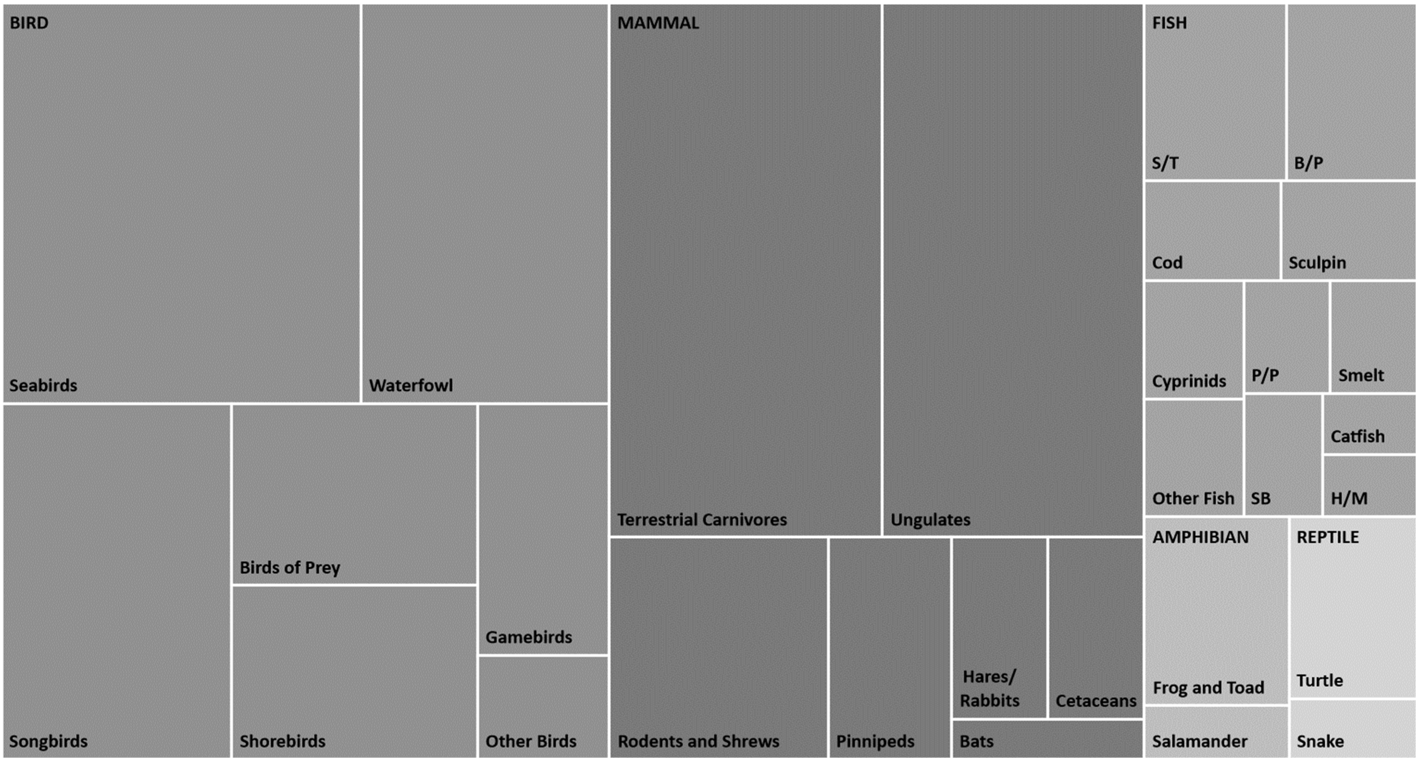

Fig. 3. Breakdown of the taxonomic representation of the manuscripts included in the scoping review. The data are shown as a treemap; the area of each rectangle is proportional to the number of manuscripts. S/T, salmon and trout; B/P, bass and perch; P/P, pike and pickerel; H/M, herring and mackerel; SB, sticklebacks).

Location

The number of publications was similar across geographic regions (Fig. 2). Few studies sampled across regions (34/388; 9%) or provinces/territories (51/388; 13%). Quebec–Atlantic (14/34; 41%) was the most common pairing in manuscripts that sampled across regional jurisdictions, followed by Prairies–British Columbia (11/34; 32%) (Supplementary Table SIV). New Brunswick–Nova Scotia (14/51; 27%) was the most common pairing in manuscripts that sampled across provincial/territorial jurisdictions, followed by Manitoba–Alberta (12/51; 24%) (Supplementary Table SIV). Sampling/study within a single province/territory was common across all species categories; of the species categories with at least 10 manuscripts, sampling across jurisdictions was described most frequently for waterfowl (18/51; 35% publications with sampling in ≥ 2 provinces/territories).

Most manuscripts (266/305; 87%) described a nonurban location of data collection with only a small proportion described as occurring within an urban area (11/305; 4%) or a combination of urban and not urban (28/305; 9%). However, many manuscripts did not describe the area in sufficient detail to be categorized (83/388; 21%) (Supplementary Table SI).

Authorship and funding affiliation

Academic and federal governmental organizations were common in both author affiliation and funding categories (Supplementary Table SI). Of the manuscripts with a federal government author affiliation, 10% (17/177) included multiple federal agencies, whereas 26% (77/298) of the manuscripts with

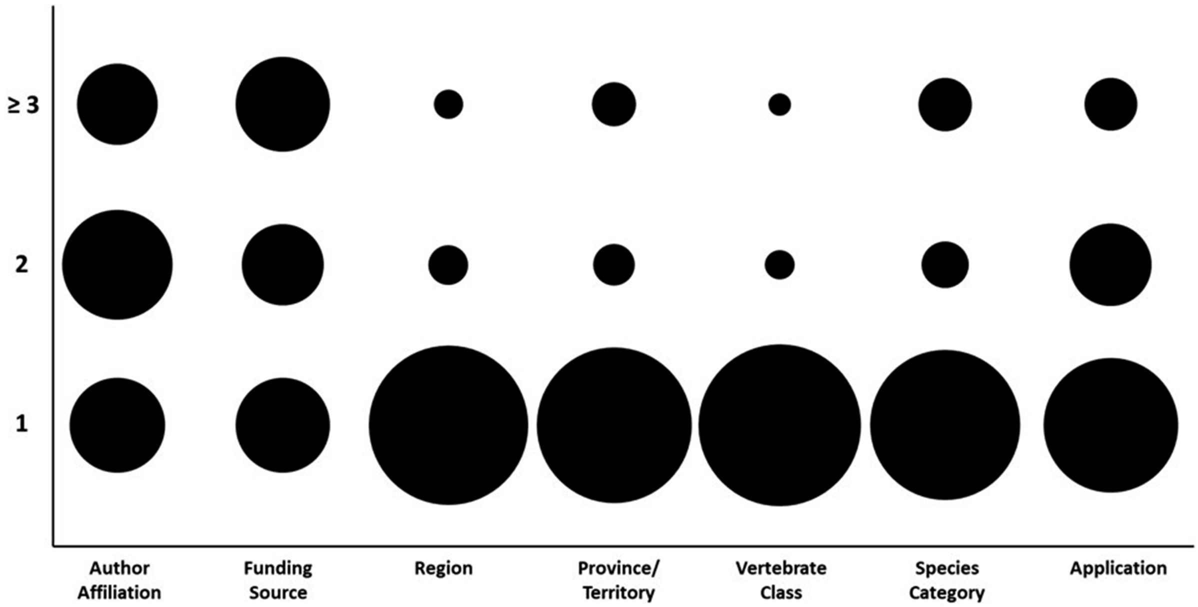

Fig. 4. Relative proportion of manuscripts with 1, 2, or 3+: author affiliations, funding sources, region in which study occurred, province/territory in which study occurred, taxonomic focus (vertebrate classes and species category), and application as described in the manuscript (where available). The data are shown as a bubble chart; the area of each disk is proportional to the number of studies. (Author and funding affiliations include: academic, federal government, Indigenous, international academic, international government, municipal government, private, provincial government, other; vertebrate classes include: mammal, bird, reptile, amphibian, fish; species categories include: bats, terrestrial carnivores, pinnipeds, hares and rabbits, rodents and shrews, ungulates, cetaceans, birds of prey, songbirds, gamebirds, seabirds, shorebirds, waterfowl, other birds, bass and perch, cyprinids, catfish, cod, pike and pickerel, salmon and trout, smelt, sticklebacks, sculpin, herring and mackerel, other fish, frog and toad, salamander, snake, and turtle; application as described in the manuscript include: wildlife health, domestic animal health, environmental health, public health, wildlife health, other).

a Canadian academic author affiliation included multiple Canadian academic institutions. Notably, affiliations with provincial governments and private organizations were commonly associated with funding while affiliation with Indigenous organizations/governments was present in a small percentage of manuscripts across author and funding categories (Supplementary Table SI).

Cross-affiliation authorship (261/388; 67% publications with ≥2 different categories of author affiliation) and cross-affiliation funding (218/343; 64%) was relatively common (Fig. 4). Academic–federal government was the most common author affiliation pairing followed by academic–provincial government (Supplementary Table SIII). Of the species categories with at least 10 manuscripts, those featuring frogs/toads (7/14; 50%) and songbirds (20/42; 48%) were the most likely to have author(s) associated with a single affiliation category, whereas manuscripts that featured rodents and shrews (12/25; 48%) and birds of prey (10/20; 50%) were most likely to indicate funding from a single source category.

Objectives

The most common objectives included: detection/quantification of pathogen, disease, or toxicant (158/388; 41%) and population or fatality count (132/388; 34%) (Supplementary Table SI). Of the surveillance literature with a detection/quantification objective, bird, reptile, and fish sampling predominantly focused on toxicants whereas amphibian and mammal sampling tended to be pathogen-focused (Table 2). The toxicants studied fell into 6 major categories: metals and minerals (41/97; 42%), industrial (41/97; 42%), flame retardants (30/97; 31%), insecticides (27/97; 28%),

Table 2. Summary of 158 manuscripts included in a scoping review of published wildlife health surveillance in Canada, with a detection/quantification of pathogen, disease, or toxicant objective stratified by vertebrate class.

Category	No. (%)[a] of studies				
	Amphibian (*n* = 4)	Bird (*n* = 88)	Fish (*n* = 6)	Mammal (*n* = 63)	Reptile (*n* = 3)
Pathogen					
Any pathogen	3 (75.0)[b]	19 (21.6)[c]	0 (0.0)	38 (60.3)[d]	0 (0.0)
Viral	1 (25.0)	11 (12.5)		16 (25.4)	
Bacterial	0 (0.0)	4 (4.5)		14 (22.2)	
Protozoa	0 (0.0)	2 (2.3)		5 (7.9)	
Prion	0 (0.0)	0 (0.0)		1 (1.6)	
Fungal	2 (50.0)	0 (0.0)		0 (0.0)	
Parasitic	1 (25.0)	3 (3.4)		12 (19.0)	
Molecular analysis of pathogen	1	9	0	20	0
Toxicant					
Any toxicant	1 (25.0)	67 (76.1)	6 (100.0)	22 (34.9)	2 (66.7)
Flame retardants	0 (0.0)	20 (22.7)	3 (50.0)	6 (9.5)	2 (66.7)
Metals and minerals	1 (25.0)	27 (30.7)	4 (66.7)	10 (15.9)	0 (0.0)
Insecticides	0 (0.0)	20 (22.7)	2 (33.3)	5 (7.9)	1 (33.3)
Industrial	0 (0.0)	29 (33.0)	2 (33.3)	8 (12.7)	2 (66.7)
Plastic	0 (0.0)	5 (5.7)	0 (0.0)	0 (0.0)	0 (0.0)
Rodenticides and avicides	0 (0.0)	2 (2.3)	0 (0.0)	1 1.6)	0 (0.0)
Disease[e]	1 (25.0)	0 (0.0)	0 (0.0)	9 (14.3)	1 (33.3)

[a]Percentages do not add up to 100% as multiple categories may apply to one manuscript.
[b]Pathogens: viral (Ranavirus), fungal (*Batrachochytrium dendrobatidis*), parasitic (*Ribeiroia ondatrae*).
[c]Pathogens: viral (Avian bornavirus, Avian influenza, West Nile, Newcastle disease), bacterial (*Pasteurella multocida*, *Escherichia coli*, *Clostridium botulinum* (type E botulism)), protozoal (*Toxoplasma gondii*), parasitic (*Protocalliphora*, *Cytoditidae*, *Ereynetidae*, *Rhinonyssidae*, *Turbinoptidae*, *Ixodes scapularis*).
[d]Pathogens: viral (Hooded seal herpesvirus, Harp seal herpesvirus, Ringed seal herpesvirus, Aleutian mink disease, Canine parvovirus, Feline panleukopenia, Canine adenovirus, Canine distemper, Jamestown canyon, Snowshoe hare, Bovine herpesvirus-1, Bovine parainfluenza-3, Bovine viral diarrhea, Rabies, Porcine reproductive and respiratory syndrome, Porcine circovirus-2, Transmissible gastroenteritis, Swine influenza, Torque teno, Ovine herpes-2, Parapox), bacterial (*Escherichia coli*, *Salmonella enterica*, *Mycobacterium bovis*, *Leptospira* spp., *Mycobacterium avium paratuberculosis*, *Francisella tularensis*, *Clostridium difficile*, *Actinomyces* spp., *Actinobacillus pleuropneumoniae*, *Mycoplasma hyopneumoniae*, *Lawsonia intracellulari*, *Brucella* spp.), protozoal (*Cryptosporidium*, *Giardia* spp., *Toxoplasma gondii*, *Coccidia* spp., *Trypanosoma*), prion (Chronic wasting disease), parasitic (*Cephenemyia jellisoni, Cephenemyia phobifera*, *Lineolepis parva*, *Staphylocystoides*, *Trichinella* spp, *Parelaphostrongylus odocoilei, Protostrongylus stilesi, Moniezia, Eucoleus boehmi, Echinococcus canadensis, Umingmakstrongylus pallikuukensis, Varestrongylus eleguneniensis*, *Toxascaris leonine*, *Taeniid*, Anoplocephalid, Capillarid, Hookworm, *Sarcocystis* sp.).
[e]Diseases: encephalitis, lymphadenitis, nasal pathology, thyroid pathology, liver pathology, orchitis, cardiovascular, physical injury, physical abnormality.

plastic/marine debris (6/97; 6%), and rodenticides and avicides (3/97; 3%). The pathogens were largely viral (29/68; 43%), bacterial (21/68; 31%), and parasitic (20/68; 29%) with far fewer sampling for protozoa (6/68; 9%), fungi (2/68; 3%), or prions (2/68; 3%). Of the 65 manuscripts that measured one or more pathogens, molecular analysis/strain typing was described in less than half (31/65; 48%).

Approximately 20% (87/388) of manuscripts included in the review positioned the topic within the context of relevance for management/policy action (noted within the introduction), and another 20% (72/388) included management/policy-related objectives or objective-specific applications for management/policy (noted specifically within the objective paragraph) (**Supplementary Table SI**). Approximately one-third of manuscripts provided specific recommendations for future action based on manuscript conclusions (not including recommendations for further research) (**Supplementary Table SI**).

Approximately one-third of manuscripts framed the application of their data/study findings at the intersection of at least two sectors, with the majority focusing on the application for a single sector, namely wildlife health (**Fig. 4**) (**Supplementary Table SI**); the most common cross-sectoral applications described include: wildlife health – environmental health (84/388; 22%) and wildlife health – public health (43/388; 11%) (**Supplementary Table SV**).

Methodology

Regardless of taxa, the majority of manuscripts (>80%) included in this review described active surveillance methods with data collected by the researcher (**Table 3**). Passive surveillance methods (28/388; 7%) or methods that incorporated citizen or hunter submissions (12/388; 3%) were uncommon (**Supplementary Table SI**). Mammal-focused manuscripts described passive surveillance methods (18/176; 10%) most frequently, and the largest proportion of mammal (52/177; 29%) and fish (10/35; 29%) focused manuscripts described data collection by individuals other than the researcher (e.g., citizen, hunter; **Table 3**). At least one form of sampling requiring euthanasia was described most often in fish-focused manuscripts (14/35; 40%) and in 29% (50/174) of bird-focused manuscripts (**Table 3**). At least one form of sampling requiring handling of live animals was described most frequently in mammal-focused manuscripts (69/178; 39%) but was used in the largest proportion of reptile- (11/14; 79%) and amphibian-focused (7/16; 44%) manuscripts. Observation of live animals, as a sampling method, was described in 50% of both amphibian- and reptile-focused manuscripts and occurred in 43% of bird-focused manuscripts (74/174; **Table 3**). Animal samples collected from the environment (e.g., feces, feathers/hair, tracks) were described infrequently across vertebrate class; mammal-focused manuscripts were the most likely (23/178; 13%) to describe these sampling methods and amphibian (0/16; 0%) and reptile (0/14; 0%) the least likely (**Table 3**). At least 40% of amphibian-, bird-, fish-, and mammal-focused manuscripts described length of study as two or fewer calendar years (**Table 3**). Approximately 20% of bird- and mammal-focused manuscripts described three or more calendar years of sampling/study (**Table 3**). A majority (9/14; 64%) of reptile-focused manuscripts described a study length of "—three to four" calendar years (**Table 3**).

Discussion

This scoping review provides a synopsis of 10 years of published Canadian vertebrate wildlife health surveillance literature. We describe patterns related to species, location, authorship and funding affiliation, objectives, and methodology and discuss 5 areas for future growth that align with the shared goals outlined in the PCAWH framework: representativeness, expanded and diversified collaboration, community engagement, harmonization of approach, and a shift to a solutions-focused and one-health mindset.

Table 3. Summary of data collection methodology in 388 manuscripts included in a scoping review of published wildlife health surveillance in Canada, stratified by vertebrate class.

Category	No. (%)[a] of studies				
	Amphibian (n = 16)	Bird (n = 174)	Fish (n = 35)	Mammal (n = 178)	Reptile (n = 14)
Length of study (years)					
1	7 (46.7)	47 (28.0)	10 (31.3)	38 (21.8)	2 (14.3)
2	4 (26.7)	32 (19.0)	7 (21.9)	32 (18.4)	1 (7.1)
3–4	3 (20.0)	30 (17.9)	6 (18.8)	39 (22.4)	9 (64.3)
5–9	1 (6.7)	28 (16.7)	6 (18.8)	32 (18.4)	0 (0.0)
≥10	0 (0.0)	31 (18.5)	3 (9.4)	33 (19.0)	2 (14.3)
Unknown[b]	1	6	3	4	0
Surveillance method					
Active[f]	16 (100.0)	160 (92.5)	32 (94.1)	149 (84.7)	14 (100.0)
Passive[g]	0 (0.0)	10 (5.8)	0 (0.0)	18 (10.2)	
Combination	0 (0.0)	3 (1.7)	2 (5.9)	9 (5.1)	0 (0.0)
Unknown[b]	0	1	1	2	0 (0.0)0
Data collector					
Citizen	0 (0.0)	11 (6.4)	5 (14.3)	14 (7.9)	0 (0.0)
Hunter/trapper/fisher	0 (0.0)	7 (4.1)	5 (14.3)	38 (21.5)	0 (0.0)
Researcher	16 (100.0)	162 (94.2)	30 (85.7)	150 (84.7)	14 (100.0)
Other[c]	0 (0.0)	1 (0.6)	0 (0.0)	0 (0.0)	
Unknown[b]	0	2	0	1	0 (0.0)0
Sampling					
Carcass collection					
Dead/harvested by hunter	4 (25.0)	39 (22.4)	8 (22.9)	60 (33.7)	6 (42.9)
Euthanized for study[d]	3 (18.8)	50 (28.7)	14 (40.0)	21 (11.8)	1 (7.1)
Live Animal					
Required handling	7 (43.8)	43 (24.7)	9 (25.7)	69 (38.8)	11 (78.6)
Observational	8 (50.0)	74 (42.5)	8 (22.9)	64 (36.0)	7 (50.0)
Environmental[e]	0 (0.0)	10 (5.7)	1 (2.9)	23 (12.9)	0 (0.0)

[a]Percentages do not add up to 100% as multiple categories may apply to one manuscript.
[b]Not included in denominator for percentage calculation.
[c]Industry.
[d]Includes egg collection.
[e]Environmental: bird (nests, feces, feathers), fish (redds), mammal (feces, dropped antlers, tracks, urine, hair, cratering sites, beaver lodges).
[f]Researcher-initiated sample submission.
[g]Observer-initiated sample submission.

Representativeness: species and geographic focus

Cross-taxonomic manuscripts were uncommonly identified in this review suggesting that the shift toward an eco-regional approach, where multiple components of an ecosystem are integrated rather than considered individually, is not yet well reflected in the wildlife health surveillance literature (Manley et al. 2004). Notably, a few studies included in this review highlighted the importance of a multi-species approach. For example, Heard et al. (2008) stated "...most telemetry-based animal movement studies have tracked individuals of one species, but there is increasing recognition of the importance of understanding multi-species movement patterns and interactions". Similarly, Montevecchi et al. (2012) stated "our research highlights the necessity of conducting multi-year and multi-species studies when using top predators to detect important marine areas and emphasizes the importance of identifying and characterizing biological hotspots based on knowledge, not only of prey behavior and distribution, but also on predator flexibility in response to change". Critical thought is needed as to how a multi-species approach can be practically integrated in the design of future wildlife health surveillance and research strategies.

Consistent with previously reported trends (Magle et al. 2012), most manuscripts identified in this study focused on birds and (or) mammals, while manuscripts about fish, reptiles, and amphibians were much less common. Under-representation of certain taxa in the manuscripts identified warrants attention particularly in light of the growing number and scale of threats to vulnerable populations (e.g., diseases affecting biodiversity, highly disturbed wetland habitat) and documented gaps in knowledge of the population that prevent species rankings or setting of targets (e.g., Target 14 in the 2020 Biodiversity Goals and Targets for Canada).

Charismatic fauna in relatively undisturbed and less populated settings tend to attract financial and social support, whereas the perception of many species of urban wildlife is that of nuisance animals and reservoirs of disease (Stephen et al. 2018). Accordingly, wildlife health surveillance that promotes the health of urban species has not traditionally been prioritized (Stephen et al. 2018), and this was evident in the manuscripts included in this review of which only 11% occurred in urban areas. Urban wildlife face different conditions and challenges compared with their nonurban counterparts (Magle et al. 2012; Murray et al. 2019), and the cumulative impacts of urbanization on wildlife health are not well understood. There is growing recognition of the interconnections between the health of people and animals in shared environments, and as urban areas in Canada expand and grow, the frequency of human–wildlife interactions and conflict is expected to increase. Recent literature advocates for urban wildlife health surveillance that incorporates a harm-reduction approach (Stephen et al. 2018), and initiatives like the Vancouver Rat Project (cwhcbc.com/vancouver-rat-project), underscore such an evolution.

While it is acknowledged that the urban categorization used in this review is an over-simplification of a nuanced metric, it is important to note that a substantial proportion of manuscripts did not provide sufficient detail for a categorization to be made. Even with clearly documented descriptions of study location, the variation in methodology used to determine urban gradients can hinder cross-study comparisons and our ability to generate consensus theory (Moll et al. 2019).

Expanded and diversified collaboration

Consistent with previous findings (Magle et al. 2012), most manuscripts identified in this review had academic corresponding-author affiliations, followed distantly by authors from the federal government. As publications represent a primary communication mechanism in academia, this finding is perhaps not surprising nor is it a negative situation. Manuscripts describing sample collection across provincial/territorial jurisdictions were rare and most were between neighboring provinces/territories. While most wildlife species are managed at the provincial/territorial level, interdisciplinary and cross-boundary partnerships can provide an important balance of perspectives that helps integrate multiple facets of wildlife health issues. Cross-boundary collaboration is crucial to the protection and recovery of migratory species or species with large home ranges (e.g., brown bears) that can experience a wide variety of conditions and protections as they move. Relying solely on "local" data may lead to an over-simplification of conclusions, and changes occurring over a broad geographic scale or related to factors occurring well away from where sampling activities are being undertaken, may be missed.

The importance of advancing collaborative partnerships and building coordinated networks is a point of focus in a number of wildlife health strategies (Federal, Provincial, and Territorial Governments of Canada 2018; USGS National Wildlife Health Center 2019) and multi-jurisdictional management action is already occurring for a number of priority species (Environment and Climate Change Canada 2018), but the creation of coordinated multidisciplinary networks is challenging. Building trust and shared goals takes time. The lack of a regulatory framework that supports cooperation and coordination across levels of government adds to inherent logistical challenges. The PCAWH outlines an agenda for expanding the national collaborative network of wildlife health experts to facilitate the development of such relationships and integrate other complimentary skillsets that lie outside of the wildlife health field (e.g., social sciences and science communication). Cross-affiliation authorship was common in the manuscripts identified, especially between federal and academic researchers. Unfortunately, a more detailed breakdown of affiliation would have been required to enumerate the presence of collaborative networks. While the national focus of this review prevented the evaluation of transnational cooperation, the importance of such cross-jurisdictional collaboration is of note particularly for migratory species.

It is acknowledged that the scope of consultation employed for each project may not be evident in the published manuscript; an approach other than a scoping review would be needed to develop a full understanding of the processes employed in each situation. However, looking forward, a continued emphasis on expanding the boundaries of existing partnerships (e.g., academic–federal government) will be integral for a modernized approach to wildlife health surveillance. As we work to build these relationships, we must also look for ways to increase the relevancy of wildlife health to more people while remaining accountable to those individuals and communities (e.g., Indigenous communities) that maintain a close relationship with the land and wildlife populations.

Collaboration continued: Indigenous partnership and traditional ecological knowledge

The meaningful role of Indigenous governments and traditional ecological knowledge (TEK) in monitoring and sustaining healthy wildlife populations has been described in the published literature, recognized in the PCAWH, and specifically highlighted under Canada's Biodiversity Target 15 (Federal, Provincial, and Territorial Governments of Canada 2018; Environment and Climate Change Canada 2019; Parlee et al. 2012). This scoping review identified only a handful of manuscripts that described the incorporation of TEK or indicated specific Indigenous authors or funding affiliations (e.g., co-management boards, self-governing regional governments). To the extent that these elements reflect inclusion of Indigenous Peoples in wildlife health surveillance, our findings are consistent with Canada's most recent national report to the Convention on Biological Diversity that outlines "progress towards target but at an insufficient rate" in reference to Target 15 (Environment and Climate Change Canada 2019). There are ongoing discussions about the value of diverse knowledge systems working together and the benefits of including quantitative and qualitative data in wildlife health projects (Peacock et al. 2020). According to Parlee et al. (2012, p. 2) "the integrated perspective offered by Cree Elders and harvesters is a strength of this alternative knowledge system and is also arguably necessary for understanding the cumulative nature of environmental change".

Community engagement

Citizen science and community-based monitoring were reported infrequently in the manuscripts included in this review, with the large majority of manuscripts reporting data collection by researchers. The benefits of engaging the broader public in wildlife health and conservation initiatives is increasingly recognized in policy documents at all levels. For example, Target 19 of Canada's National Biodiversity Strategy specifically aims to increase community participation in biodiversity conservation activities and empowering the stewards of natural resources is a guiding principle of the PCAWH (Federal, Provincial, and Territorial Governments of Canada 2018; Environment and Climate Change Canada 2019). To engage the community and other disciplines in wildlife health surveillance initiatives, we must increase recognition of the value of wildlife and the important interconnections among wildlife, human, and environmental health. Community engagement offers an opportunity for shared learning and promotes a sense of empowerment and responsibility for wildlife health by including the community as an integral part of surveillance and conservation efforts. There are many citizen-science platforms that collect wildlife data in Canada (e.g., Frogwatch, Wild Whales, Moose Tracker App) that were not captured in this review. It is possible that these data and platforms are less likely to appear in publication format or perhaps the date range of this review did not capture data gathered through newer platforms. It is encouraging that participation/effort in voluntary citizen-science monitoring programs is reportedly increasing in Canada (Environment and Climate Change Canada 2019) and that community-based wildlife monitoring strategies have been successfully implemented (Carlsson et al. 2015). Certainly, citizen science is not without limitations, which are well described; however, the opportunity to harness the community to collect wildlife health data on a temporal and spatial scale that may otherwise not be possible is a strategy that deserves attention (Lawson et al. 2015).

Harmonization of approach

The multi-sector, multi-determinant nature of wildlife health issues has led to the development of a variety of approaches and methods for collecting data relevant to wildlife health across disciplines and species. Numerous manuscripts in this review highlighted the limitations of varied methods and metrics used to frame and analyze outcomes: Avery-Gomm et al. (2016, p. 79) stated "we suggest that the disparity in prevalence rates between these two otherwise similar studies was more likely due to a difference in methodology than regional differences, highlighting the importance of adopting standardized methods," and Swan et al. (2015, p. 870) indicated "one of the major limitations of this study, as well as others, is a lack of congruity with similar research in terms of the variables recorded... these differences can make direct comparison of species or populations more difficult." A call for standardized methodologies and case definitions is not new; more recent are calls for consensus concepts of wildlife "health" and a common understanding of the factors that influence the health of species at the individual and population level (Stephen 2014; Patyk et al. 2015). Initiatives to articulate a shared definition (Hanisch et al. 2012) and situationally tailored working definitions (Patyk et al. 2015) of wildlife health have been published. Metrics that facilitate comparison of health status across wild populations/locations and support the integration of diverse perspectives of wildlife health into existing management objectives, are needed. A shift toward a determinants of health model, as used in the public health field, has emerged as a promising framework that is scalable and can be applied across species (USGS National Wildlife Health Center 2019; Wittrock et al. 2019). A determinants of health framework may also provide a mechanism to identify factors influencing health that may be well-studied while others may still require assessment.

Efforts to integrate emerging techniques and technologies can help standardize observations, increase coverage (spatial and temporal), and decrease long-term costs. This review identified an opportunity to expand the use of animal samples collected from the environment (e.g., hair, feces) and adopt other innovative noninvasive sampling techniques. A disproportionate number of bird and fish studies used lethal sampling methodology and environmental sampling was infrequent across all taxonomic groups. Of course, notable exceptions were identified: Bechshoft et al. (2015, p. 1315) indicated "Claws, feces, feathers, breath, hair, vibrissae, photographic identification, and paw prints are being used to increase our knowledge of diet, size, distribution, abundance, sex, genetic makeup, hormonal status, pollution load, and other variables in free-ranging wildlife." Such noninvasive methods of assessing wildlife health status have been investigated in the literature; samples that can be obtained without interaction between species and researchers are valuable particularly for species at risk where permit requirements, population numbers, and cryptic behavior may present obstacles for capture as well as in circumstances where capture may lead to adverse effects (Buttler et al. 2011). Novel technologies have also been explored; for example, the use of smartphones to monitor wildlife–vehicle collisions (Olson et al. 2014), unmanned aerial vehicles (Chabot and Bird 2015), and environmental DNA (Bohmann et al. 2014). However, coordinated employment of innovative technologies is paramount to prevent compounded issues with cross-study incomparability considering the diversity of technologies and rapid change in the field.

A shift to a "solutions-focused" and "One Health" mindset

In so far as the value of wildlife health data are assessed in the wider context of relevance for policy/management, the link to action is particularly relevant. Most of the manuscripts identified in this review were "problem-focused" and aimed to characterize a particular issue (e.g., pathogen prevalence). This is consistent with other literature that found a majority of wildlife health publications are problem-focused and not structured around a path to solutions (Peters et al. 2019) although we acknowledge that how the data end up being used is often not available/communicated at the time of publication. While decisions about wildlife health issues are multi-dimensional, identifying management-oriented objectives and consulting with end-users at all stages of the project can contribute to identifying solutions that are feasible, sustainable, and generally agreeable (Nichols and Williams 2006; Peters et al. 2019). This is not to say that basic discovery research does not have an important role in generating knowledge relevant to wildlife health. However, in the context of the wider ecological monitoring literature, of which wildlife health is one component, Pasher et al. (2013) posited that data collected for other purposes are often not useful in a management/policy context. Indeed, calls for a shift towards applied "use-inspired" and solutions-focused projects have emerged in the wildlife health literature, particularly considering limited resources (Stephen 2017; Peters et al. 2019).

While a traditional siloed approach was evident in the surveillance literature reviewed, it is noted that approximately one-third of manuscripts framed the "problem" and application of study findings at the intersection of at least two sectors namely, wildlife health and environmental health or wildlife health and public health. One Health—the intersection of animal, human, plant, and environmental health, as defined by the One Health Commission (onehealthcommission.org/)—is an approach for conceptualizing, characterizing, and communicating about issues that promotes the engagement of multiple perspectives toward optimal and sustainable preventive or corrective solutions. While it may not be necessary to specifically incorporate each component to meet the standards for One Health methodology as outlined in recent guidelines (Davis et al. 2017), a One Health mindset can be incorporated in the design of wildlife health surveillance, monitoring, and research and in the communication of study objectives and findings. As aptly put by Stephen (2021, p. 31), "Without understanding how to frame a health problem across species and generations so that it resonates with those people who need to act to protect the many types of health in a place, cooperative, collaborative action that protects the health of one species without harming the health of others cannot be achieved".

Limitations

While we attempted to carry out a thorough search of the peer-reviewed published literature, it is likely that our key word search missed manuscripts that may have been relevant. The inclusion of additional broad terms such as bird and mammal was not pursued considering the available time and resources. The authors proceeded with the assumption that the term wildlife would appear within at least one field of a manuscript that pertained to a wild species; however, this may not be the case in all instances. Furthermore, there is a subjective element to inclusion/exclusion criteria and the development of the categorization framework. The nature of the data charting process is such that manuscripts were coded according to our interpretation of published information; the underlying motivations and meanings may not always be easy to discern or not fully expanded upon due to word limits. It is acknowledged that the authors relied on the number of papers to describe patterns and generate conclusions; there are alternate metrics that would be interesting to consider (e.g., intensity of surveillance effort) that were outside the scope of this review.

Inclusion of grey literature (e.g., government reports) would undoubtedly improve our understanding of the topic and is an important caveat to the methodology employed in this review. A similar review of the grey literature is an important area of future study and would provide further insight into publication bias in this field and how these biases compare between the peer-reviewed and grey literature. Nevertheless, the authors considered peer-reviewed published reports to be an important indicator of patterns in the field of wildlife health and this assumption is supported by its use as a metric in the evaluation of progress towards Canada's Biodiversity Targets (Environment and Climate Change Canada 2019).

Few studies identified in this scoping review met all elements of the definition of surveillance as outlined by Hoinville et al. (2013) namely, "continuous or repeated measurement" and "linked with action to mitigate risk". In practice, the distinctions among surveillance, monitoring, and research projects may be blurred as they include similar key features (e.g., data collection, analysis, interpretation, and dissemination of findings) and in fact, all three may be relied upon to contribute to meeting wildlife health surveillance objectives.

Conclusion

Many research teams have devoted significant resources, expertise, and important findings toward the protection and promotion of wildlife health in Canada. The goal of this review was to identify patterns in the Canadian wildlife health surveillance literature and highlight opportunities for growth that integrate perspectives and opinions from wildlife health professionals and align with the goals outlined in the recent PCAWH strategy. Indeed, clear patterns were identified related to species and geographic focus, authorship and funding affiliation, and objectives and methodology that align with the challenges facing wildlife health programs in Canada described in the PCAWH. Five primary areas were identified that have the potential to propel the field of wildlife health: attention to representativeness (e.g., species and geographic focus), expanded and diversified collaboration, community engagement, harmonization of approach, and a shift to a solutions-focused and One Health mindset. This scoping review provides a synopsis of 10 years of Canadian wildlife health surveillance, challenges us to envision the future of successful wildlife health surveillance, and provides a benchmark from which we can measure change.

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Author contributions

JAG, EJP, MR, DLP, and CMJ conceived and designed the study. JAG, MR, and DB performed the experiments/collected the data. JAG, MR, and DB analyzed and interpreted the data. JAG, EJP, MR, DB, DLP, and CMJ drafted or revised the manuscript.

Competing interests

The authors declare no competing interests.

Data availability statement

All relevant data are within the paper and in the Supplementary Material.

Supplementary material

The following Supplementary Material is available with the article through the journal website at doi:10.1139/facets-2021-0027.

Supplementary Material 1

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