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Contributions of scale: What we stand to gain from Indigenous and local inclusion in climate-health monitoring and surveillance systems

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Abstract

Understanding how climate change will affect global health is a defining challenge this century. This is predicated, however, on our ability to combine climate and health data to investigate the ways in which variations in climate, weather, and health outcomes interact. There is growing evidence to support the value of place- and community-based monitoring and surveillance efforts, which can contribute to improving both the quality and equity of data collection needed to investigate and understand the impacts of climate change on health. The inclusion of multiple and diverse knowledge systems in climate-health surveillance presents many benefits, as well as challenges. We conducted a systematic review, synthesis, and confidence assessment of the published literature on integrated monitoring and surveillance systems for climate change and public health. We examined the inclusion of diverse knowledge systems in climate-health literature, focusing on: 1) analytical framing of integrated monitoring and surveillance system processes 2) key contributions of Indigenous knowledge and local knowledge systems to integrated monitoring and surveillance systems processes; and 3) patterns of inclusion within these processes. In total, *24* studies met the inclusion criteria and were included for data extraction, appraisal, and analysis. Our findings indicate that the inclusion of diverse knowledge systems contributes to integrated climate-health monitoring and surveillance systems across multiple processes of detection, attribution, and action. These contributions include: the definition of meaningful problems; the collection of more responsive data; the reduction of selection and source biases; the processing and interpretation of more comprehensive datasets; the reduction of scale dependent biases; the development of multi-scale policy; long-term future planning; immediate decision making and prioritization of key issues; as well as creating effective knowledge-information-action pathways. The value of our findings and this review is to demonstrate how neither scientific, Indigenous, nor local knowledge systems alone will be able to contribute the breadth and depth of information necessary to detect, attribute, and inform action along these pathways of climate-health impact. Rather, it is the divergence or discordance between the methodologies and evidences of different knowledge systems that can contribute uniquely to this understanding. We critically discuss the possibility of what we, mainly local communities and experts, stand to lose if these processes of inclusion are not equitable. We explore how to shift the existing patterns of inclusion into balance by ensuring the equity of contributions and justice of inclusion in these integrated monitoring and surveillance system processes.

Introduction

Understanding how climate change will affect global health is a defining challenge this century (1,2). This is predicated, however, on our ability to combine climate and health data to investigate the ways in which variations in climate, weather, and health outcomes interact. Information from satellite observations and geographical information systems, for example, have improved our understanding of changing patterns in climate, environments, and biodiversity (3). These patterns can play an important role in driving incidence and changing distributions of several vector-borne diseases of public health importance (e.g. malaria, dengue, Rift Valley fever, schistosomiasis, Chagas disease, and leptospirosis) (3–5). Though critical for global health and climate policy, such research requires access to climate data and health data that are available for similar geographical areas and periods of time to be integrated and compared.

Despite this need for data integration, the fields of climate change and public health have evolved very different approaches and systems for data generation and evaluation over time. Surveillance reflects the systematic and repeated cycle of observation, data analysis, and the conversion of data into actionable information for implementing change and improving population health (6). While the main motivation of a surveillance system is to collate information that drives action (6), every system has bespoke objectives and methods. Each surveillance system is designed to gather high-quality and timely information at a resolution and in a format relevant to the particular context (6). This results in substantial differences between climate observation systems and health surveillance systems design; owing to the different temporal and spatial scales at which climate and health are typically and often differentially investigated. For instance, while climate observation systems might monitor weather or climate variation in relatively large areas over years, decades, and centuries (e.g. change in sea surface temperature over 2 centuries), public health surveillance systems more frequently focus on monitoring mortality or prevalence or incidence of morbidity of individuals, populations, or smaller spatial units over days, months, and years (e.g. weekly malaria counts in urban neighbourhoods). Rarely are climate and health datasets opportunistically complementary in resolution and availability. These differences mean that combining climate and public health data is challenging, and difficult to integrate if developed separately.

There is growing evidence to support the value of place- and community-based observation, monitoring, and surveillance efforts (7–14), which can contribute to improving both the quality and equity of data needed to understand the impacts of climate change on health (15–19). Just by working within existing expertise and capacities of local communities to collect information that is both familiar and accessible to them brings benefit to both the quality of data processes as well as the principled ethics of monitoring and surveillance systems research (14,17,18,20–23). Embedded within Indigenous knowledge systems (IKS) and local knowledge systems (LKS), place- and community-based observation, monitoring, and surveillance also have the ability to provide locally accurate, precise, reliable, and valid information about the health impacts of environmental and climatic change that can be used in complementarity with instrumented observation networks and coordinated with other information systems (10,15,24).

The inclusion of multiple and diverse knowledge systems has been recognized as a key element in robust decision-making for informing policy, science, and social action (25–28). This is also true in the context of climate change (29–31), where information produced with, and by, diverse knowledge systems has been documented as an important source for informing, and improving, decision making processes in climate-health policy, practice, and research (32,33). The inclusion of local and Indigenous knowledges in such decision-making processes is leading to a growing recognition of rights and realization of justice for peoples and communities (34–36); with value of this inclusion extending into areas of resource management, environmental policy, and climate change adaptation (32,37–41). The United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the Intergovernmental Panel on Climate Change (IPCC) consider both Indigenous knowledges and local knowledges as key elements of the social and cultural systems that influence observations of, and responses to, climate change (42).

Both Indigenous knowledges and local knowledges encompass personal experience and observation, explanatory inference and interpretation, as well as indirect experience and oral history to continuously generate collective, inter-generational, place-based knowledges (43–45). However, Indigenous and local also refer to distinct knowledge systems (i.e. Indigenous knowledges can be local; local knowledges are not always Indigenous). Indigenous knowledges refer to the understandings, skills, and philosophies developed by societies with long histories of interaction with their natural surroundings. The United Nations Sub-Commission on the Promotion and Protection of Human Rights explains how Indigenous knowledge systems include scientific, agricultural, technical, and ecological knowledges that pertain to a particular people and its territory (46). Indigenous knowledges embody a web of relationships within a specific ecological context and evolve through dynamic inter-generational transmission (35). Indigenous scholar Battiste (2005) describes Indigenous knowledges as systemic, "covering both what can be observed and what can be thought"; comprising "the rural and the urban, the settled and the nomadic, original inhabitants and migrants" (35)(pp. 4). For many Indigenous peoples, Indigenous knowledges inform decision-making about fundamental aspects of life, from day-to-day activities to longer term actions and governance. These knowledges are integral to cultural complexes, which also encompass language, systems of classification, resource use practices, social interactions, values, ritual, and spirituality (42). Local knowledges refer to the understandings, skills, and theories developed by individuals and populations that are specific to a place (42). While local knowledges can also inform decision-making about fundamental aspects of life, from day-to-day activities to longer-term actions and governance, they are not necessarily based on a specific culture or embedded in a wider system.

Despite well-established recognition of the importance of diverse knowledge systems, sources of information, and scales of evidence, however, the practical integration of these systems has been more difficult to operationalize (23,36,47,48). Some constraints of integration include informational, financial, institutional, technological, linguistic, educational, political, cultural, epistemological, ontological, and human factors (11,25,49–51). Existing literature reviews on integrated climate and health monitoring and surveillance have begun to highlight diverse benefits and challenges of knowledge diversity and inclusion (15,16,19). As such, a comprehensive or systematic review of the contributions and inclusion of diverse knowledge systems in climate and health monitoring and surveillance would make a necessary contribution to the existing body of literature. In this review, we systematically map the published literature on integrated climate-health monitoring and surveillance systems. We examine the inclusion of diverse knowledge systems in climate-health literature, focusing on: 1) analytical framing of integrated monitoring and surveillance systems (MSS) processes 2) key contributions of Indigenous knowledge systems (IKS) and local knowledge systems (LKS) to MSS processes; 3) patterns of inclusion within these MSS processes.

Methods

We conducted a systematic review and evidence synthesis of published literature on integrated monitoring and surveillance for climate change and public health. We applied the reporting standards for systematic evidence syntheses (ROSES) forms to guide the review process (52). The literature search aimed to systematically and transparently identify empirical papers that: 1) documented monitoring and/or surveillance system; 2) integrated climate and health information or data; 3) included locally inclusive or participatory approaches; and 4) included multiple and diverse knowledge systems in MSS processes.

Data Source and Document Selection

Search terms were included as either topic or key terms: [“community*”OR “local*” OR “place*”] AND [participat*] AND [monitor* OR observ* OR surveill*] AND [health OR disease OR wellbeing OR incidence] AND [climat* OR weather OR season* OR meteor*]. A final search string was used to search the academic citation databases of Scopus®, PubMed®, and Web of Science™ in November 2018 (Table 1). The search was completed again in July 2019 to include publications from November and December 2018. Web of Science™ search results include international databases from a range of disciplines, including health, agriculture, food science, technology, biology, ecology, and zoology: BCI, BIOSIS®, KJD, MEDLINE®, RSCI, SciELO. Search results were limited to 2006-2018. This limit was determined using the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4; Working Group II) effective cut-off date for submission of supporting literature (October 2006) to focus on recent and up-to-date climate-health research. We did not restrict articles by language. The reference management software Mendeley was used to extract and store lists of citations identified in the initial searches. Lists were merged and duplicates removed, then transferred to the review software Covidence.

Table 1: Final search strings utilized in Scopus®, PubMed®, and Web of Science™ databases.

Database	Search String
Scopus®	KEY (community*) OR KEY (local*) OR KEY (place*) AND KEY (participat*) AND (KEY (monitor*) OR KEY (observ*) OR KEY (surveill*) AND KEY (health) OR KEY (disease) OR KEY (wellbeing*) OR KEY (incidence) AND KEY (climat*) OR KEY (weather) OR KEY (season*) OR KEY (meteor*))
PubMed®	((((((((local*[Title/Abstract]) OR community*[Title/Abstract]) OR place*[Title/Abstract]))) AND participat*[Title/Abstract]) AND ((((monitor*[Title/Abstract]) OR observ*[Title/Abstract]) OR surveill*[Title/Abstract]))) AND ((((climat*[Title/Abstract]) OR meteor*[Title/Abstract]) OR weather[Title/Abstract]) OR season*[Title/Abstract])) AND ((((health[Title/Abstract]) OR disease[Title/Abstract]) OR incidence[Title/Abstract]) OR wellbeing[Title/Abstract])

Web of Science™	TS=(community* OR local* OR place*) AND TS=(participat*) AND TS= (monitor* OR observ* OR surveill*) AND TS=(health OR disease OR wellbeing OR incidence) AND TS=(climat* OR weather OR season* OR meteor*)

Predefined selection criteria (Table 2) were applied in the first round of screening based on the title and abstract of each study. MSS were defined by related activities, stages, and processes involved in the systematic and repeated cycle of observation and informed response pertaining to changes within a climate-health boundary. The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5; Working Group II) Chapter 11 was used to define how climate change (i.e. meteorological shifts, or environmental disruptions departing from the average) impacts on human health, or contributes to ill health (i.e. shifting patterns of disease; displacement of populations; heat-related injury, illness and death; crop failure; reduced food production; induced undernutrition)(53). As per IPCC AR5, eligible health impacts due to climate included three dominant causal pathways: direct exposure; indirect exposure mediated through natural systems; and socio-economic disruption mediated through human systems (53). Although our review targeted climate-health literature, we recognize that the bulk of literature relevant to climate-health does not directly document climate data, rather proxies of climate variation. Therefore, we included papers focusing on meteorological and environmental variations that are presumed to be proxies of climate change along the causal pathways impacting health. Definitions and examples of core components for climate, health, and impact pathways are given in Table 3. These boundaries were defined *a priori* and based on scoping the literature before conducting the search. We recognize that there are different terminologies used within inclusive and participatory approaches in place-and community-based literatures; from "consultation" to "participation", to "engagement", to "leadership". We have decided to use the term "inclusion" to reflect this spectrum of scaled levels and applications. Potentially relevant articles were retained for full-text screening and assessed based on the inclusion criteria in Table 2. Following the selection of eligible articles from our search, reference tracing was undertaken to identify additional relevant articles either cited by (forward tracing) or citing (backwards tracing) included articles. This is a method used to search for reports of studies that may not have been indexed in the electronic databases originally searched. A secondary reviewer, unfamiliar with the review beyond the specific inclusion criteria, screened a random sample of returned studies (n = 64).

Table 2: Inclusion and exclusion criteria applied to the screening and selection of studies.

INCLUSION CRITERIA	EXCLUSION CRITERIA
(1) Empirical paper that clearly describes a monitoring and/or surveillance system (aims, objectives, context, methods, data)	(1) Does not give empirical examples of monitoring or surveillance activities
(2) Contains both health and climate related monitoring and/or surveillance data	(2) Focus of paper is not within defined climate-health boundaries

(3) Papers that substantively discuss more than one type, source, or scale of monitoring and/or surveillance data	(3) Describes only one type, source, or scale of data
(4) Papers that substantively discuss elements of inclusive and participatory approaches involved in monitoring and/or surveillance system processes	(4) Inclusive or participatory approach is absent/indeterminate

Table 3: Definition and examples of core review components used to guide document selection.

CORE COMPONENT	BOUNDARY DEFINITIONS	EXAMPLES (INCLUDED)	EXAMPLES (EXCLUDED)
CLIMATE	Climatic variables, as well as environmental and meteorological proxies	Unseasonable environmental conditions (i.e. river flow, sea-ice formation, flooding, forest fires) or unusual changes in weather (i.e. heavy precipitation, drought, extreme temperatures)	Environmental or meteorological conditions with no indication of change/variability
	Indicating change/variability that departs from the average	Changes in wildlife populations (seasonal distribution) Changes in vegetation / plant populations (seasonal flowering and budding) Changes in river flow and sea-ice formation	
HEALTH	Outcomes and determinants of human health and wellbeing Including access, availability, quantity, and quality of food, water, air, shelter, and security	Incidence of heat stroke / exhaustion Disruption to livelihoods and cultural practices Loss of homes and livestock Incidence of disease in wildlife and plant populations used for subsistence	Disruption to animal populations (vector-borne, zoonotic diseases) without explicit link to human health Vector-borne zoonotic diseases with sensitivity to change / variability that doesn't depart from the

			average (i.e. seasonal distribution)
PATHWAYS OF IMPACT	Adaptation pathways (within IPCC WGII) Not mitigation (within IPCC WGI)		Anthropogenic influences and emissions (i.e. impacts of air quality on health as a result of traffic related air pollution; impacts of ecosystem depletion on health as a result of over-fishing, urbanization, human encroachment)
	Direct impacts	Unintentional injury/fatality, including frostbite and hypothermia, as a result of unusual weather	
	Indirect impacts (mediated through natural systems)	Food insecurity due to reduced harvest and consumption of wildlife as a result of increasing temperatures and decreased winter severity	Impacts on ecosystems (i.e. coral reef resilience, river composition, forests diversity) without explicit link to human adaptation pathways
	Socio-economic disruption (mediated through human systems)	Changes in social activities, travel, and changes in work or other activities explicitly linked to wellbeing as a result of moderating effects on temperatures	

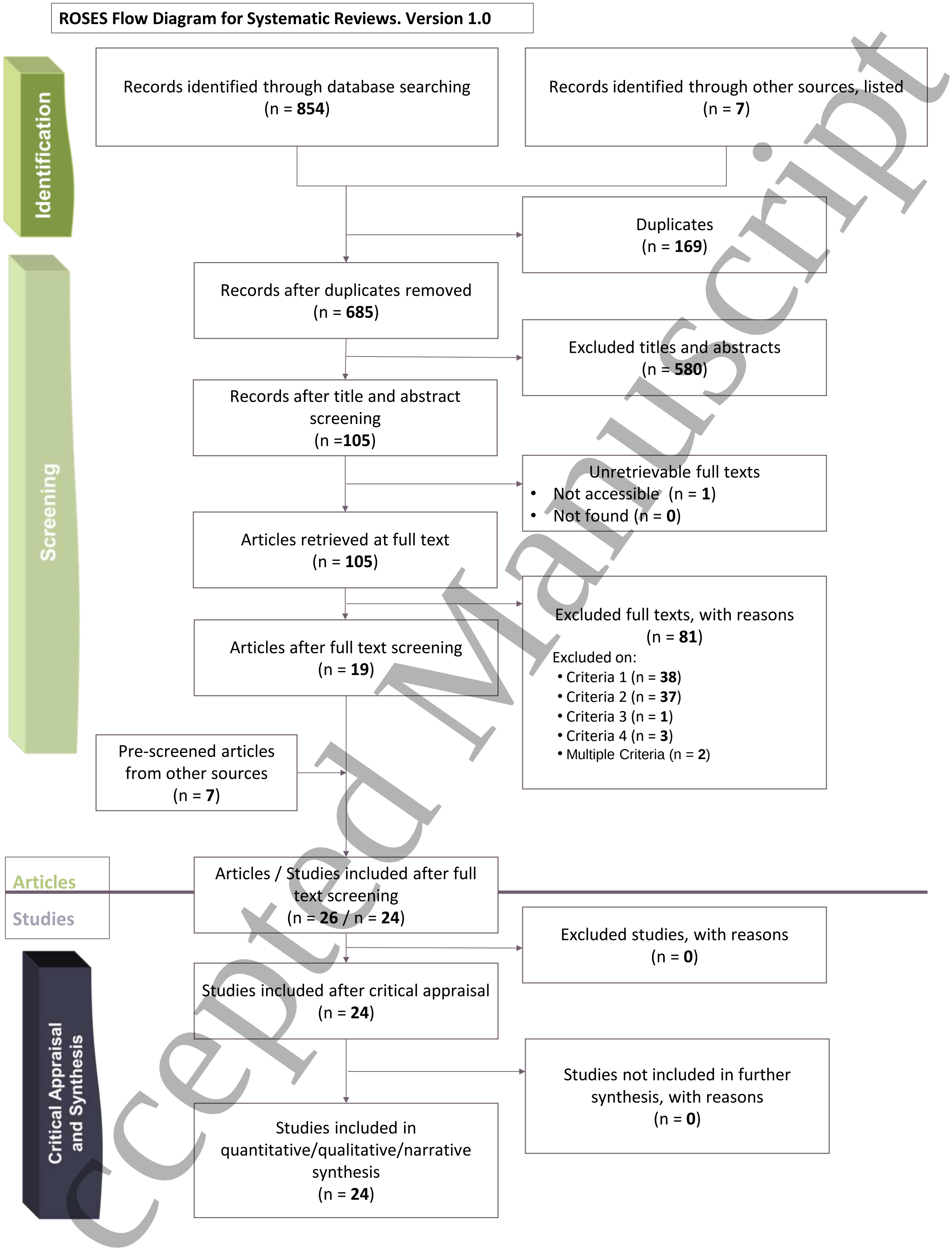

Figure 1: Flow diagram of study identification, screening, eligibility, and inclusion.

*Format follows Haddaway et al. (2017) ROSES flow diagram for systematic reviews, version 1.0.

Data Extraction

Information from each of the included studies was extracted using a data extraction form. Theory and definitions taken from public health surveillance evaluation approaches (6,54,55), quality assessment methods (56,57), as well as community-based participatory monitoring (7–14,17,19) were used to design the data extraction form. The form was piloted and refined before undertaking the final extraction process. Data extracted for each study included general bibliographic information and details of the integrated climate-health MSS: who was involved (expertise, background, experience); where was the MSS (geographic region and scale); what was the aim of the MSS (climate-health focus, causal pathway, measures); and what were the methods used. Consistent with the focus of our review, we also extracted information pertaining to: the limitations of the existing MSS; the contributions of IKS and LKS to MSS processes; the insight resulting from the inclusion of multiple and diverse sources, scales, and types of information in MSS.

Appraisal of Information Quality

A quality appraisal of included studies was performed. Given the challenges of performing critical appraisal for assessing methodological limitations—for example, the considerable variability of quality appraisal in qualitative research—Munthe-Kaas et al. (2018) recommend using an approach that fits the review question and synthesis methods to assess the methodological strengths and weaknesses of the reviewed studies (58). This was an important consideration as many of the studies included in our review use participatory approaches and mixed methodologies. Therefore, we chose the Mixed Methods Appraisal Tool (MMAT), which has been developed and applied in public health and medical research for the appraisal stage of systematic reviews that include qualitative, quantitative, and mixed methods studies (59). The MMAT is an evidenced-base critical appraisal tool developed from literature reviews, user interviews, and expert consensus (60). We adapted the present version of the MMAT (2018) to include additional questions from the population health evidence cycle; specifically those relating to issues of utility, internal validity, and practical implications (61). The adapted tool is included in the supplementary materials (1).

Analytic Framework Development

During the analysis, an analytic framework of MSS processes was iteratively developed (Figure 2). Firstly, we identified key stages of integrated monitoring and surveillance along with examples of associated activities: initiation (i.e. problem definition); system design (i.e. tool and technique development); implementation (including data collection); analysis (including interpretation); evaluation, dissemination (including feedback of findings); and action (including utility and application of findings). Then, we aggregated this information into three overarching processes of MSS: detection; attribution; and action. Associated attributes of MSS data quality assessment measures and outcomes retrieved from public health surveillance evaluation approaches (6,54,55) and quality assessment methods (56,57) were applied alongside these stages and processes to assist with the coding in further analyses of studies included in the review. This framework helped to extract information about MSS activities reported in studies and characterize the extent to which the literature describes the inclusion of diverse knowledge systems in broader processes of climate-health MSS. Within the focus of our evidence synthesis, we used inductive qualitative coding and content analysis to identify key contributions and patterns of inclusion. These findings are evidenced below in text with direct quotes and examples from included studies.

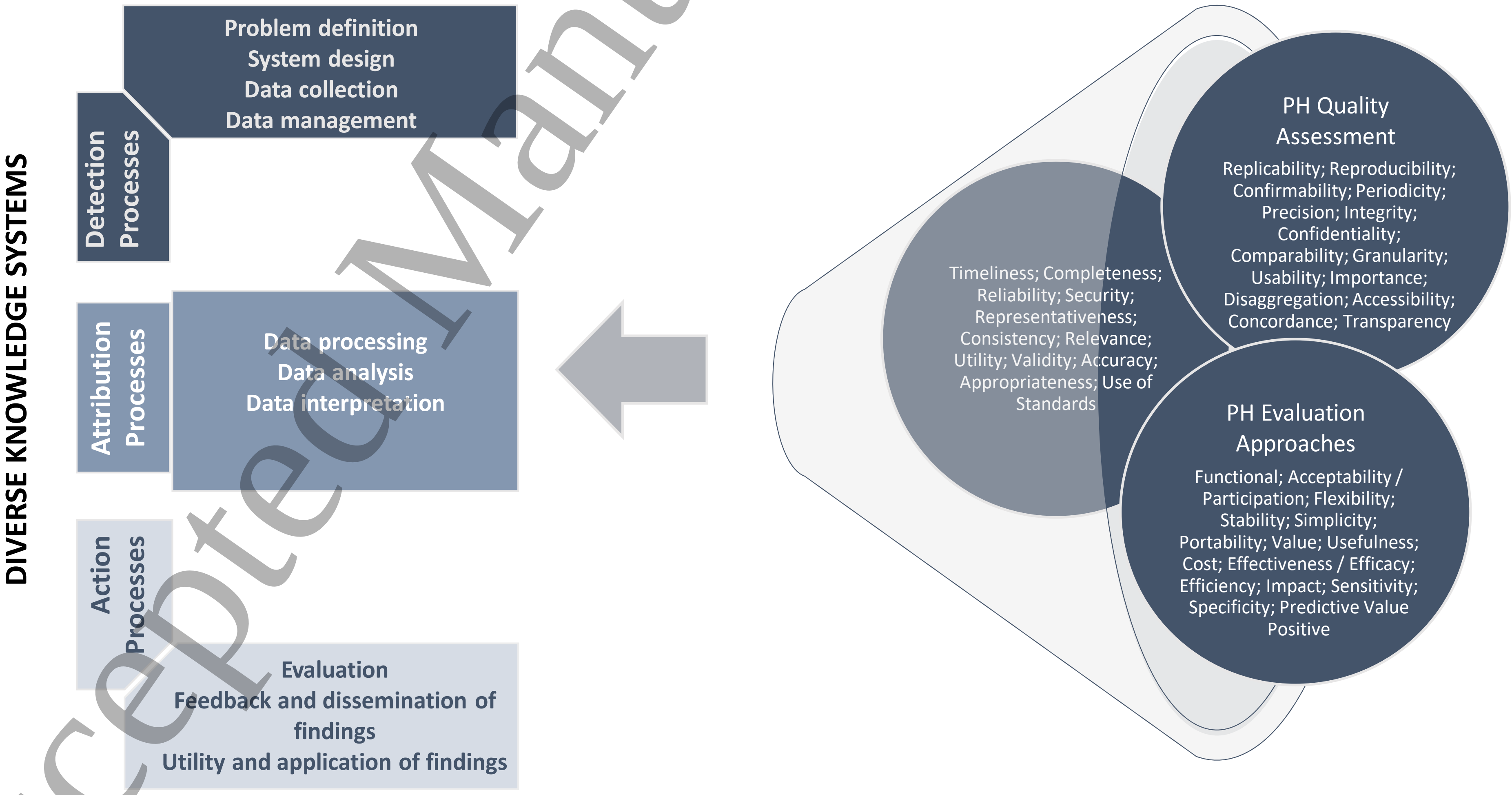

Figure 2: Analytic framework developed of integrated monitoring and surveillance system processes.

Confidence of Evidence Assessment and Summary

A Confidence in Evidence from Reviews of Qualitative Research tool developed by The Grading of Recommendations Assessment, Development, and Evaluation (GRADE-CERQual) was applied to a summary of each review finding (58,62–67). We used this approach to assess the extent to which our review findings are a reasonable representation of integrated climate-health MSS. This process is recommended to support the use of findings from qualitative evidence syntheses in decision making processes such as guideline and policy development (62). Refer to the supplementary materials (2) for the complete metadata and evidence profiles with explanations contributing to CERQual judgements. Judgements are made based the underlying confidence in evidence and have been assessed as per the level of concern with methodological limitations, adequacy, relevance, and coherence. Definitions for each component, as well as levels of confidence, can be found in Table 4 (62,63). No or very minor concerns are considered those *unlikely* to reduce confidence in a review finding; minor concerns are considered those that *may* reduce the confidence; moderate concerns are considered those that will probably reduce confidence; and serious concerns are considered *very likely* to reduce the confidence in a review finding (62,63).

Table 4: Definitions of CERQual components and levels of confidence used to assess review findings.

Component

Methodological Limitations	The extent to which there are concerns about the design or conduct of the primary studies that contributed evidence to an individual review finding.
Adequacy	An overall determination of the degree of richness and quantity of data supporting a review finding.
Relevance	The extent to which the body of evidence from the primary studies supporting a review finding is applicable to the context (perspective or population, phenomenon of interest, setting) specified in the review question.
Coherence	An assessment of how clear and compelling or supportive the fit is between the data from the primary studies and a review finding that synthesizes that data.

Level of Confidence

High	It is highly likely that the review finding is a reasonable representation of the phenomenon of interest.
Moderate	It is likely that the review finding is a reasonable representation of the phenomenon of interest.
Low	It is possible that the review finding is a reasonable representation of the phenomenon of interest.
Very Low	It is not clear whether the review finding is a reasonable representation of the phenomenon of interest.

Results

Descriptive Findings of Climate-Health Monitoring and Surveillance Systems

19 studies met the selection criteria; with 7 additional studies identified through reference tracing. In total, 24 studies were included for data extraction, appraisal, and analysis (Figure 1). Approximately three quarters (75%) of the total documents included from our search were published since 2013, the latter half of our search period, underscoring the recent rise of publications in this field (Figure 3). The greatest proportion of studies (n=11) represented MSS in the Arctic, with the remaining

distributed between (non-Arctic) North America (n=5), South Asia (n=5), South America (n=2), and Northwest Asia (n=1) (Figure 4a).

One third of MSS were motivated by a combined climate-health perspective, while a greater proportion (n=11) were focussed mainly on climate-oriented information (Figure 4b). In the reviewed studies, there was representation of MSS information that related to all three of the identified climate-health causal pathways (Figure 4c). The majority (n=23) of MSS monitored indirect exposures of climate change impacting on health, as mediated through natural systems and modified by environmental, ecosystem, and social factors (Table 3). Many MSS investigated multiple exposure pathways; 14 combined 'indirect exposure' and 'social and economic disruption', while one looked at all three pathways ('direct exposure', 'indirect exposure', and 'social and economic disruption').

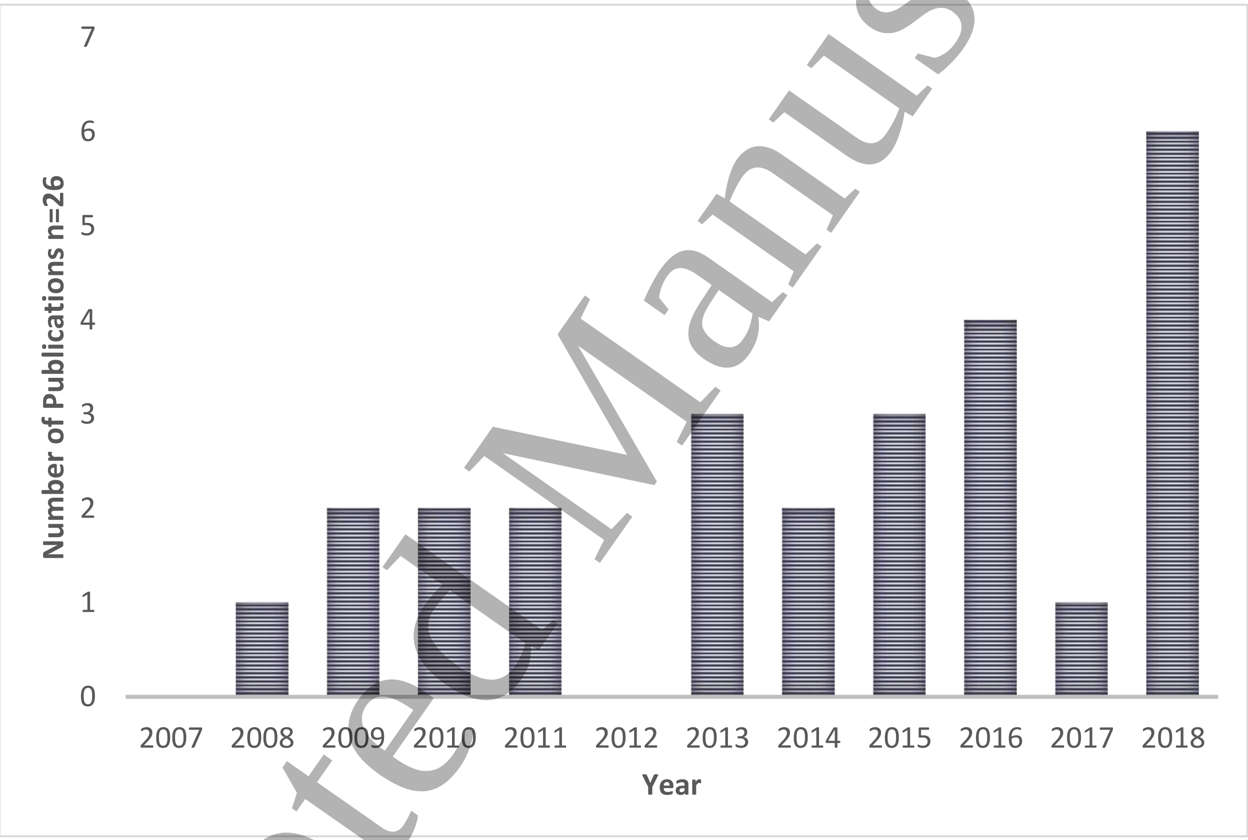

Figure 3: Distribution of articles included in the review by year of publication.

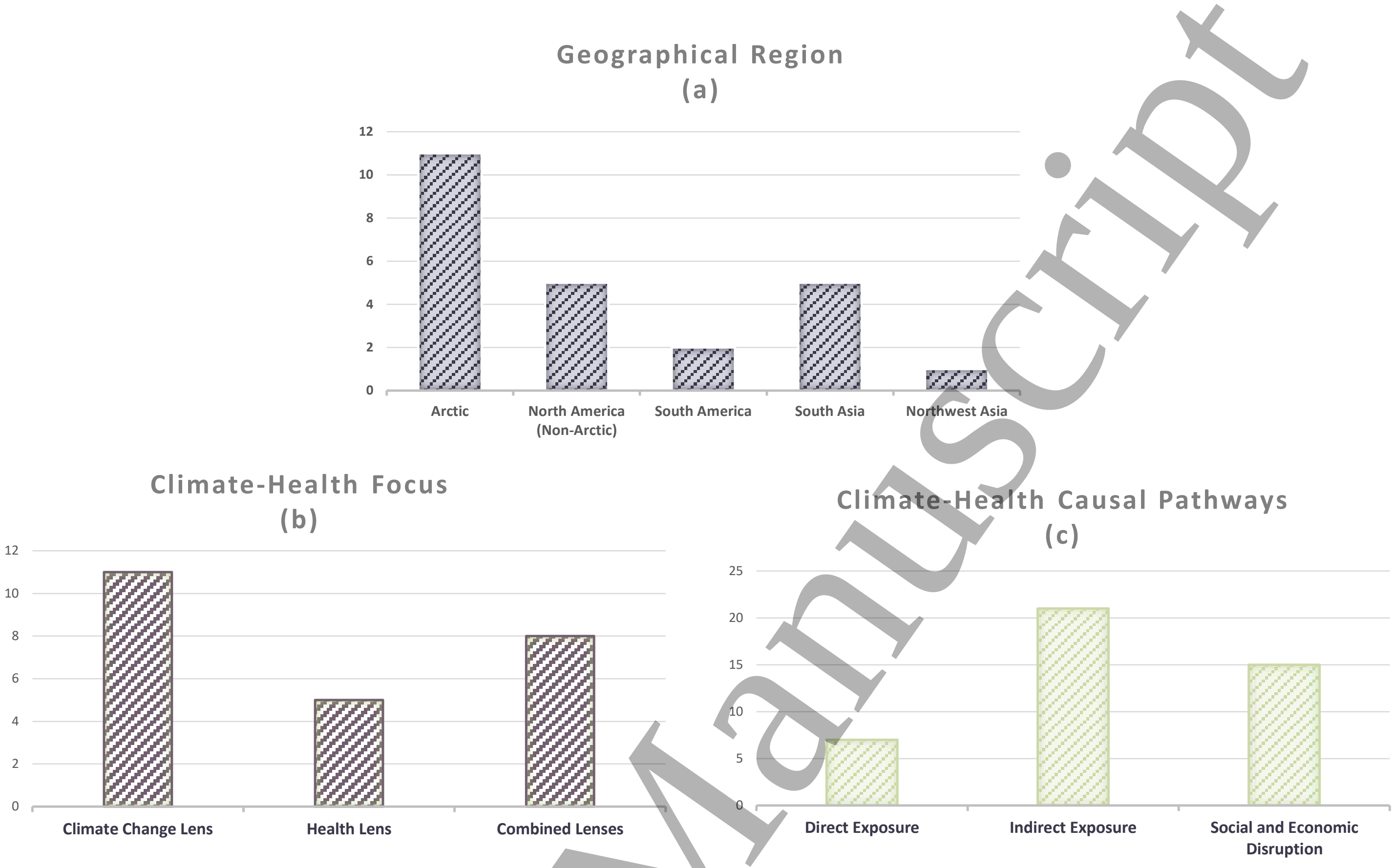

Figure 4. Studies presented by geographical region (a); climate-health focus (b); and climate-health causal pathways (c).

A majority of studies (n=23) indicated that inclusion of IKS and LKS occurred in the monitoring and collection of data (Figure 5). In four of these studies, monitoring and collection were the only stage where IKS and LKS were involved, while more than a quarter (n= 6/23) indicated the inclusion of IKS and LKS in every recorded stage and activity of MSS. Over two-thirds of studies (n=17) local and Indigenous experts and knowledge systems led or participated in the design of the monitoring project or surveillance system, and of those, 10 included evidence of IKS and LKS included in, or leading, the initiation of a monitoring system, defining the problem, and focusing the initial research. One example is from Iverson et al. (2016), where a large number of newly deceased birds were observed by local Indigenous harvesters (68). This spurred a collaborative investigation with monitoring and collecting tissue samples for laboratory analysis, which eventually confirmed an outbreak of Avian Cholera. Another example from Doyle et al. (2013), discussed how "observations made by Tribal Elders about decreasing annual snowfall and milder winter temperatures over the 20th century initiated an investigation of local climate and hydrologic data by the Tribal College"(69). This same study was the only one to have local Indigenous principal investigators and lead authors. Another study, Parlee et al. (2014), included local Indigenous co-authors on the publication (70).

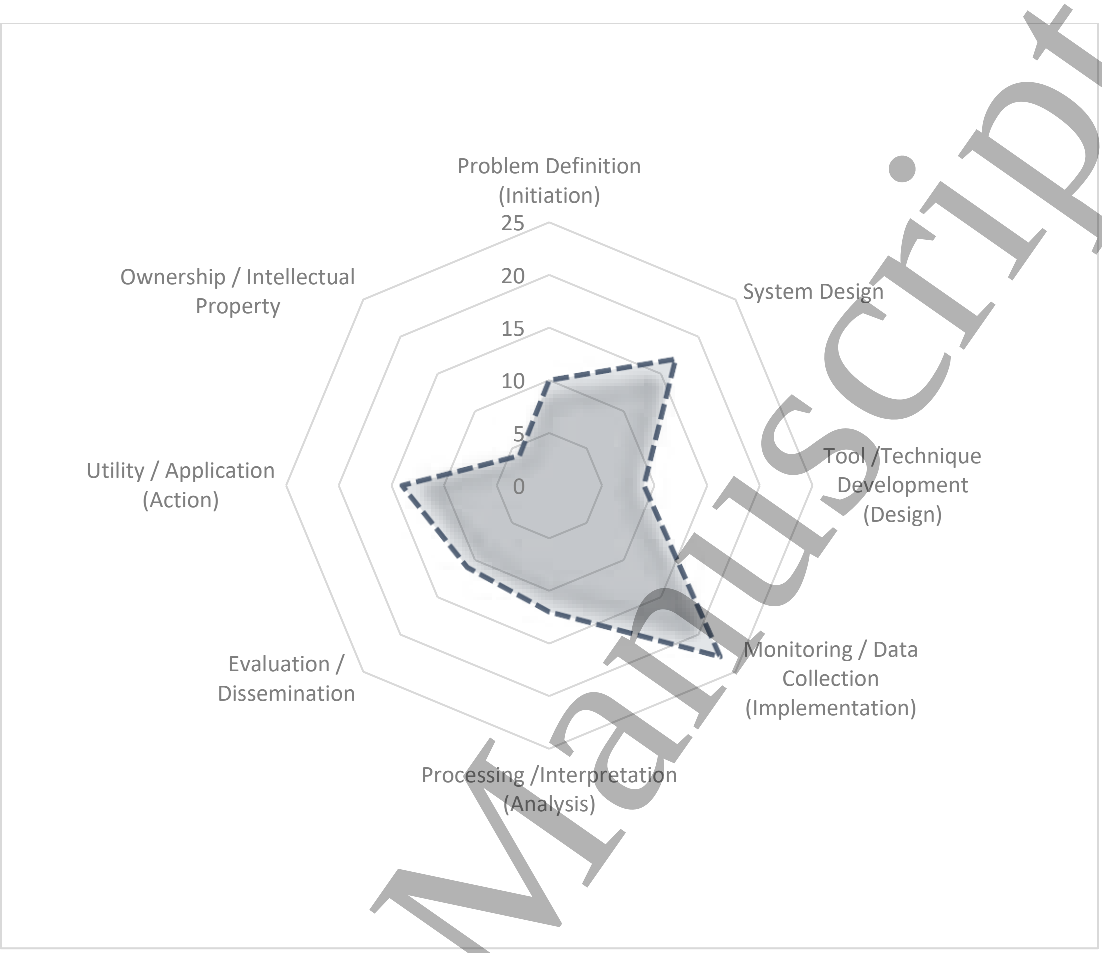

Figure 5: Inclusion of diverse knowledges across stages and activities of monitoring and surveillance systems. Axis lines reflect the number of studies reporting the inclusion of diverse knowledge systems broken down by previously identified MSS stages and activities: initiation; design; implementation; analysis; dissemination; evaluation; action. Data were also captured for studies that specified tool or technique development, as well as those that referred to data ownership or intellectual property.

We found that over one third of studies (n=9) specified the inclusion of diverse knowledge systems in the development of a monitoring and collection tool or technique; including a fire potential index (71); safe practice guide for land and ice travel (72); and infrastructure assessment tool (73). Driscoll et al. (2016) offer a description of their process, and its value, for co-producing a surveillance tool; “developing first metrics, then an instrument, and finally a primary data collection protocol in collaboration with both content-area experts and residents of rural and isolated villages in Alaska has resulted in a valid and actionable surveillance tool for use in a region of the country with few secondary data-sources” (20).

Only four studies made reference to the ownership of information or intellectual property of IKS and LKS (71,73–75). One study referred to this as a “previously unapproachable avenue for research, in that the communities were aware that all resources stayed in the community, and any potential intellectual property that may arise from [a discovery] remained in the hands of the communities” (74).

Mustonen (2015) reflected on the past, present, and ongoing insider-outsider dynamics claiming that "the notion of community ownership of visual histories and materials [data] is on the rise. This means that some aspects of cultural, communal visual histories may be off-limits for those actors, such as researchers, who come from outside a specific community"(75). Hendricks et al. (2018) discuss how an emphasis on local ownership of the data collected (and assets produced) could positively affect morale, enthusiasm, and perhaps even impact the quality of the data (73).

Contributions of Including Diverse and Multiple Knowledge Systems

In most studies, the contributions of diverse and multiple knowledge systems focussed on MSS processes that improve a system's ability to detect and gather information; including defining the problem, designing the system, collecting data, and managing data. Fewer studies demonstrated how IKS and LKS contribute to MSS processes that improve a system's ability to attribute, process, interpret the information gathered. Again, few studies evidenced how IKS and LKS contribute to MSS processes that improve a system's ability to invoke action and response. Table 5 presents a summary of the key contributions of diverse knowledge systems to a variety of MSS processes. This evidence is further interpreted by applying our analytic framework, which relates key contributions to MSS processes through corresponding impacts on quality attributes and outcomes (6,54–56).

Table 5: Contributions of diverse knowledge systems to integrated monitoring and surveillance system processes.

	Contributions to Monitoring and Surveillance System Processes	Impact on Monitoring and Surveillance System Quality & Outcomes	Examples	References
1. Detection Processes *Defining the problem; Designing the system; Collecting and Managing the data*	1.1 Definition of meaningful problems	Acceptability; Relevance; Utility; Appropriateness	Local observations about decreasing annual snowfall and milder winter temperatures initiated the scientific investigation of climate and hydrologic data	(45)(76)(77)(68)(78)(69)(79)(75)(70)(70)
	1.2 More representative data	Accuracy; Validity; Predictive Value; Sensitivity; Relevance	Experiential knowledges gained through daily environmental interactions and dependence Capturing interactive, complex, and contextual health-environment-climate relationships	(73)(70)(45)(75)(80)(81)(72)(82)(83)(84)(85)(78)(86)(87)(76)(69)(79)
	1.3 More responsive data	Timeliness; Flexibility	Indigenous harvesters identify an outbreak of Avian Cholera in previously unmonitored populations and locations	(68)(45)(85)(76)(75)(80)(71)(73)(72)
	1.4 Reduces selection and source-dependence biases	Credibility; Internal Validity; Confirmability; Reliability	Parallel, regionally distributed local observations of declining snowfall provide multiple data points and are invaluable in the absence of weather stations	(68)(70)(88)(83)(45)(89)(85)(71)(76)(82)(72)

2. Attribution Processes *Processing and Interpreting Data*	2.1 More comprehensive data	Sensitivity; Completeness	Local observations of sea-ice conditions provide measurements of ice thickness with the sensitivity needed to determine if ice is safe to walk or drive on for subsistence activities Conveying finer spatial scale; greater detail than coarser general models and predictions; longer temporal scale; greater range of longitudinal data required for analysis	(83)(79)(72)(86)(85)(68)(70)(88)(90)(80)(82)(69)(45)(71)(73)(81)(76)
	2.2 Reduces scale-dependence bias	Transferability; External Validity; Confirmability; Reliability	The transmission of vector-borne diseases in spatial scales that exceed the limits of the insect vector and/or parasite dispersion	(71)(70)(85)(90)(83)(79)(45)(69)(76)(81)(86)(80)(72)
3. Action Processes *Reporting, Disseminating, and Using the Results*	3.1 Multi-scale policy development	Usefulness; Utility; Efficacy; Impact	Using integrated climate-health monitoring systems to create political and economic pressures and safety concerns	(69)(91)(80)(79)(74)(76)
	3.2 Long-term future planning	Usefulness; Utility; Efficacy; Impact	Using local monitoring and surveillance data to inform local and regional wildlife and resource management	(69)(71)(86)(91)(45)(70)(73)(85)(74)(81)(76)(78)(83)(80)(72)(79)
	3.3 Immediate decision making and prioritization	Timeliness; Efficiency; Impact; Utility	Locally led efforts made air pollution and environmental health a municipal priority	(68)(86)(91)(84)(76)(85)(45)(81)(74)(73)(78)(80)(72)(79)
	3.4 Effective knowledge-information-action pathways	Acceptability; Efficacy; Impact; Relevance; Utility; Appropriateness	Using local knowledges about soil conditions, water distribution, farming and environmental practices to adapt scientific approaches	(69)(89)(76)(86)(85)(91)(75)(74)(73)(78)(80)(72)(79)

Key Insight 1: Improving the Detection of Climate Change and Health Impacts

Reviewed studies highlighted the potential for IKS and LKS to contribute to the definition of meaningful problems, as well as the collection of more representative and meaningful climate-health data. Local and Indigenous experts in the reviewed studies include subsistence harvesters, pastoralists, farmers, Elders, observers, fire-watchers, urban residents, and rural villagers. Represented here are communities connected by an interactive and relational understanding of their environment, employing holistic mechanisms of change, and perhaps with a perspective and heightened sensitivity to detect broader climatic changes and impacts (45,70,83,84). For example, Shukla et al. (2016) note how community perceptions are developed from “daily interactions with their environment” as well as a “dependence on weather conditions to ensure sustenance”(84). Similarly, another study considered local urban residents and communities to have expert knowledge of the built environments they interact with on a daily basis (73). This included community members’ interactive understanding of local socio-political contexts, which may impact the management of physical infrastructure and thus influence the climate vulnerability of certain neighbourhoods. The community-specific, place-based, experiential knowledges of local socio-political contexts, socio-cultural values, and environment-dependent practices were exemplified in several studies (70,72,73).

Other studies indicated the potential for IKS and LKS to contribute to more responsive data collection and timely detection of monitored changes. For example, subsistence-oriented communities are well positioned to function as an early warning system that detects immediate changes in human and wildlife health, such as an outbreak of disease in moose populations or a shift in seasonal migration patterns of caribou (45,68–70). This exemplifies how the interdependence of human and animal populations brings a broader perspective and approach for situating changes in abundance, distribution, migration, and physical conditions of wildlife that have been instrumental for subsistence and survival for thousands of years (70). Another study described the indispensable and timely information generated by the “vigilant eyes” of local community forest managers, or “fire watchers”, to help establish an advance warning system for forest fires in the Indian Central Himalaya (71).

Included studies also presented the potential for local observations and alternative forms of monitoring to reduce selection and source biases that result from logistical feasibility and resource restraints. For instance, the active observations of local harvesters were indicated as useful to fill information gaps when other detection methods were not feasible (70). Mustonen (2015) highlight that scientific methods, which use remote sensing and site-specific expeditions and observations to monitor changes, provide biased information and are unable to account for the many local and Indigenous societies in these territories who continue to dwell in and occupy remote, peripheral sites, and areas outside current scientific monitoring efforts (75). Another study, by Laidler et al. (2011), demonstrates the potential of incorporating detection methods like remote sensing and radar imagery into the suite of existing traditional indicators and local tools to improve how we monitor changes within the complexity of human-animal-environmental systems like subsistence sea-ice monitoring (79). While radar and areal imagery were indicated as important methods used to measure relative sea and river ice thickness and stages of freeze-up, they do not capture locally significant levels of detail about ice conditions, changes in those conditions, and safety indicators; like when ice is thick enough to walk on versus drive on (79,82).

Key Insight 2: Improving the Attribution of Health Impacts to Climate Change

The evidenced studies provide examples of the potential for IKS and LKS to provide more comprehensive data by improving the sensitivity and completeness of existing scientific and instrumental monitoring data. For example, in addition to long-term government-operated bird monitoring stations, Indigenous Inuit Eider harvesters reported outbreaks at three locations on the northern coastline of Québec in Nunavik that researchers were unable to investigate previously as a result of logistical constraints (68). Similarly, another study evidenced how the knowledges of Indigenous and local experts and subsistence harvesters was able to provide valuable information of previously undocumented population mortality events and changes (45). In another example, Dixit et al. (2018) demonstrate how diverse demographic, health, and environmental surveillance datasets can be integrated, or “harmonized”, into one geospatial surveillance platform and processed with additional types of information from others sources such as research projects, health, facilities, and institutional records (81).

Reviewed studies evidenced the potential for IKS and LKS to contribute more comprehensive data in the absence or limits of scientific monitoring observations. For example, in the absence of weather stations, parallel and regionally distributed observations of declining annual snowfall and warming winter temperatures made by generations of Indigenous Elders provide numerous and invaluable, or otherwise missing, data points to help understand the more recent hydrological impacts of climate change experienced in streamflow and flooding (69). An epidemiological investigation to assess the impacts of climate change on syndromic health outcomes in the circumpolar north highlighted how the information contributed through community-based surveillance systems is “substantially more sensitive than more traditional passive surveillance systems” and “far more flexible than many active surveillance systems requiring participants to self-disclose their health outcomes and behaviours”(20). Another study explained how a seasonal surveillance response to Zika Virus could collect timely and comprehensive state-wide information on transmitting species of mosquitoes with the participation of multi-level stakeholder groups. Studies highlighted the value of locally acquired information, spatially scaled data, and procedural knowledges to fill some of the existing gaps of scientifically unknown and clinically uncaptured information (20,86,88).

Studies noted the potential of collective, long term, living knowledges to improve scientific monitoring data deficiencies and dearth by contributing to baseline information and datasets upon which we can track change and build future comparisons (70,79). The history and time scale of IKS and LKS epistemology extends over many generations; “strengthening the credence of their claims”(83). Such is the case in Northern Canada, where the understandings, expertise, and theories of Indigenous Elders and subsistence harvester have been developed over generations of observation and validation, and are based on an inter-dependent relationship with caribou and moose populations (70). Despite quantitative projections of climate change induced impacts requiring extended term data analysis, this connected history can provide an essential baseline for tracking changes in Arctic ecosystems and understanding the effects on wildlife and human health, as well as socio-economic impacts (70). The included literature demonstrated the potential of synergizing local and regional scaled contributions to improve the attribution of health impacts to climate change and address existing limitations of data deficiencies (such as incompleteness or incongruence). Fidel et al. (2014) note this contribution in the combination of different spatial scales of data, whereby spatial data from local reports of subsistence activities allowed the holistic exploration of human and animal adaptive responses to environmental changes over time (80).

Studies also emphasised the potential of IKS and LKS to improve how we process and interpret integrated climate-health data by reducing biases associated with the scale dependence of trended and aggregated data analyses. Such contributions include applying statistical analyses to track general trends in local observations of changes to biological resources used for subsistence over time scales (15-20 years, or one generation) as well as across large geographic scales (The Bering Sea) (80). Parlee et al. (2014) evidence how an Indigenous perspective and broader approach has the potential to situate specific health outcomes, like chronic wasting disease, in the context of scaled environmental and climatic change (70). Studies also indicated how diverse systems of knowledge and observation had the potential to inform general models and scaled predictions (83). For example, rather than analysing environmental and climatic trends using a scientific model that relies on average changes in individual variables, the LKS of pastoralist communities interprets change using a holistic mechanism that accounts for feedback between vegetation and weather; this local model allows them to integrate several variables at once and "to apply cues or rules of thumb in difficult, extraordinary situations and is founded on observations of extremes and variability" (83).

Key Insight 3: Improving Action related to Evidence on Climate Change and Health Impacts

The reviewed studies demonstrated the potential of IKS and LKS to contribute tangible benefits by improving the MSS action process related to reporting, dissemination, evaluation, and use of findings. This included evidence for contributions supporting the immediate decision making and prioritization of key issues. For example, Limaye et al. (2018) evidence how locally led planning, implementation, and evaluation of air quality monitoring networks made air pollution and environmental health a municipal priority for a city in India (91). Another study demonstrated how monitoring tools and techniques developed with Indigenous Barí and Wayúu communities in Colombia were used to influence decision making by providing "timely information to strategically plan and focus actions and resources" towards addressing climate-health issues, such as the prevention, vigilance, and surveillance of changes in vector-borne diseases (86).

Included studies evidenced the potential of IKS and LKS inclusion in the benefit of long-term future planning. Laidler et al. (2011) discuss how access to the longitudinal and time series data produced by IKS and LKS not only allows us to make analytical comparisons over time, "but also to facilitate hazards assessment, plan travel routes, and support search and rescue operations" for Inuit communities in Nunavut, Canada (79). Another example, taken from Doyle et al. (2013), is where the addition of local data to regional climate projections resulted in more "engaged community discussions" and provided a "basis for community policy development and long range planning" to reduce current and future climate-related health impacts (69). Examples of planning also included management whereby a "greater recognition of traditional systems of monitoring can result in useful empirical data for management" of wildlife and human health in connection to climate change (70). Furthermore exemplified by the application of IKS expertise and knowledge to inform regional co-management plans for muskoxen and caribou herds put forward in the National Species at Risk Act Management Plan Series (45).

Evidenced studies showed the potential of diverse knowledge systems to improve how we report, disseminate, evaluate and use integrated monitoring and surveillance information; both for community policy development as well as multi-scale policy development. Fidel et al. (2014) identify the inclusion of IKS in climate-health research as an "avenue that can bring the voices of the people to the policy-making table" and lead to adaptive strategies for responding to changes affecting the societal-ecological systems of Indigenous Arctic communities (80). Particularly when it comes to monitoring the impact of climate change on health, as in the example of the declining and unpredictable sea ice conditions, "bridging scales and knowledge systems will be essential in developing integrated monitoring systems to respond to increased political and economic pressures as well as safety concerns for travelling on or within ice-covered oceans" (79).

Included studies presented how contributions of diverse and multiple knowledge systems and scales of evidence could lead to effective knowledge-information-action pathways. One study provides evidence for how a community epidemiological health assessment, driven by local observations of extreme weather, access to land, water, food, and risk of injury, was able to "deliver direct utility" and "develop appropriate responses" with the support of the public health sector in Alaska (76). A local scaled understanding of how priority health issues relate to the type, timing, and rate of wider environmental changes, such as the premature thawing of underground food cellars spoiling food and leading to increased food insecurity, can be used to help prevent negative health outcomes (76). Contributions of IKS and LKS engagement were considered vital to both the success and stimulus of implementing integrated MSS (85,89). Even more, there was evidence to support the contributions of local capacity and innovative approaches to act and address the "new normal" and the impacts of climate change on health; as they themselves experience it (75,89). Other studies evidence how the local application, local adaptation, and even local appropriation, of monitoring and surveillance approaches presents the "greatest chance" of disseminating knowledge, stimulating action, and reducing climate-health impacts (68,89).

Confidence in the Evidence Supporting Key Insights 1, 2, 3

The assessment of evidence presented in the review studies enabled us to determine the extent to which our review findings are a reasonable representation of integrated climate-health MSS. Overall, there were moderate concerns in the evidence base contributing to each of our three keys insights regarding methodological limitations. There were minor concerns regarding the adequacy, and very minor to no concerns regarding the relevance and coherence, of evidence to support the findings that the inclusion of IKS and LKS contributes to MSS detection processes (key insight 1). Otherwise, the evidence base supporting findings that IKS and LKS contribute to MSS attribution and action processes (key insights 2 and 3) had very minor, or no concerns regarding components of adequacy, relevance, and coherence. The summary of confidence judgements in evidence supporting these key review insights are presented in Table 6. Complete metadata and evidence profiles with explanations contributing to these judgements are included as supplementary material (2).

Table 6: Summary of Confidence in Evidence Supporting Key Insights

Aim: To synthesize qualitative and quantitative evidence on the inclusion and contributions of diverse knowledge systems to integrated climate-health monitoring and surveillance systems.

Perspective: Empirical evidence of inclusion and contributions of diverse knowledge systems to integrated climate-health monitoring and surveillance systems worldwide.

Summary of review findings	Studies contributing to the review finding	CERQual assessment of confidence in the evidence	Explanation of CERQual Assessment
1. The inclusion of diverse knowledge systems can improve the detection of climate change and health impacts through: the definition of meaningful problems (finding 1.1); the collection of more representative data (finding 1.2); the collection of more responsive data (finding 1.3); and the reduction of selection and source biases (finding 1.4).	(87)(78)(82)(76)(81)(69)(85)(55)(73)(68)(79) (77)(83)(75)(70)(88)(89)(86)(71)(84)(45)(72)	Moderate confidence	Moderate concerns regarding methodological limitations, minor concerns regarding adequacy.
2. The inclusion of diverse knowledge systems can improve the attribution of health impacts to climate change through: the processing and interpretation of more comprehensive datasets (finding 2.1); and the reduction of scale dependent biases (finding 2.2).	(82)(76)(81)(69)(55)(73)(68)(90)(79)(83)(70)(88)(86)(71)(45)(72)(85)	Moderate confidence	Moderate concerns regarding methodological limitations.
3. The inclusion of diverse knowledge systems can improve the action taken based on climate-health evidence through: multi-scale policy development (findings 31.); long-term future planning (finding 3.2); immediate decision making and prioritization (finding 3.3.); and effective knowledge-information-action pathways (finding 3.4).	(78)(76)(81)(69)(85)(55)(73)(68)(90)(79)(91)(83)(75)(70)(89)(86)(71)(84)(45)(72)	High confidence	Moderate concerns regarding methodological limitations.

Key Insight 4: Improving Monitoring and Surveillance Systems with the Divergence and Discordance of Evidence

There are many potential challenges that may arise from trying to synergize the contributions of diverse knowledge systems in MSS processes. In the reviewed studies, we noted instances when authors described divergence or discordance between the methodologies and evidence of different knowledge systems.

Some studies explored the potential reasons for these discordances. For example, Marin (2010) demonstrates that local observational methods of abundant rainfall are measured by the duration of rain (83). This differs from scientific meteorological methods that measure abundance by the amount of rainfall. Since the latter does not always account for locally significant levels of change, it was recommended that recording “a combination of rain’s duration, ‘hardness’ and its impact on soil and vegetation might allow them to distinguish between significant and insignificant rains." Several studies highlight a similar discordance between different measures of ice thickness and freeze-up. Scientific methods (such as radar and areal imagery) give measures of *relative* ice thickness and record ice break-up and freeze-up as single-day events. Alternatively, local and Indigenous methods (such as Inuit sea-ice evaluations, in-situ observation, cumulative seasonal recordings, and navigation techniques) measure change in ice conditions as series of processes with safety indicators necessary for those who rely on this information for their livelihoods (75,79,82). It is useful to note how the applications of different methodologies can result in divergent measures the ‘same’ phenomenon; further still divergent interpretations of ‘significant’ change in that phenomenon.

Much the same, different applications of the same methodology can also result in a discordance of evidence. Hendricks et al. (2018) highlight this discordance between the margin of error being greater for persons “lacking extensive professional training” and collecting data using scientific technology such as laser and radar (73). Reed et al. (2018) suggest similar reasons for discordant findings, which may be due to variations between how local participants and agencies collected their information, "*our* methodology required the participation of many different contributors… [However] most participants had limited or no prior experience with [this survey method]" (88). The discordance between local observations and meteorological data using trend analysis can be exemplified for estimating changes in winter temperatures; explaining that differences in evidence could be due to confounding a decrease in daily or nightly minimum temperatures with the simultaneous increase in daily maximum temperatures (87).

Reviewed studies also highlighted potential divergences between diverse knowledge system contributions of resolution and scale. For example, the difficulty of drawing generalizations from data and attribution-related processes. Fidel et al. (2014) exemplify the challenges of aggregating Indigenous walrus harvester observations and location data from a participatory mapping exercise into a more general trend analysis: "while these [participatory mapping] techniques are extremely valuable to provide insights into adaptive actions [like ‘hotspot’ analysis] and may provide the basis for scientific discovery and discussion, they cannot create aggregate statistics of general trends" (80). While extrapolating aggregated data to establish trends remains a challenge, as mentioned previously, there is a unique expanse in geographic and temporal scale that IKS and LKS can contribute (45), which should not be discounted. Instead, we note the limitations of taking a singular scaled analytical approach, like geospatial or epidemiological, to account for the complexities of local climate-health interactions; consider, for instance, how changes in local land cover can influence micro-climate conditions in temperature, evapotranspiration, and run-off (76).

Few studies described whether these discordances were reconciled. Often, the tendency was to try and ‘resolve’ or ‘explain’ the divergence from one methodological perspective (i.e. Western scientific) by using more methodologies (i.e. employing statistical methods and trend analyses) (72,76,80). Other studies explained discordances in terms of constraints on the availability of certain resources, be they scientific or local, with inevitable compromise on how to allocate and use certain resources such as time, funding, training, and expertise. This was particularly relevant since all of studies included in the review were set in limited or constrained resource contexts, with many identified as remote. Tomaselli et al. (2018) give examples of these contextual challenges associated with monitoring and surveillance of animal and human population health in the Canadian Arctic (45). Limaye et al. (2018) suggest that, while challenging, the coordination of monitoring and surveillance stakeholders to clarify roles and avoid duplication or discordance can relieve this constraint and even reduce administrative and financial burdens (91).

Limitations and Biases

Here, we would like to discuss the limitations and biases in this review, evidence synthesis, and confidence assessment. Firstly, the literature evidenced in this review was only selected from published sources. This resulted in a publication bias with an emphasis on retrieving significant and/or positive results and may have affected the findings and key insights presented (52). We attempted to mitigate this bias by searching across multiple databases and using different search methods, like reference tracing, to search for reports of studies that may not have been indexed in the electronic databases searched. Furthermore, the focussed selection strategy and narrow eligibility criteria will have increased the likelihood of reporting bias in the evidenced data contributing to our findings and insights; again, towards significant and positive results (52). We attempted to mitigate this bias by highlighting these methodological issues in both the quality appraisal and confidence assessment processes. Given the focus of our review, we considered that many communities initiating and undertaking integrated climate-health monitoring and surveillance would not have access, opportunity, or always interest to publish empirical results. While these initiatives would not necessarily contradict the review findings, the non-identification of studies would certainly affect the contributing evidence base that we have synthesized our findings from.

More than just the quality of evidence, there are several factors that can influence the judgement of confidence in evidence(92). One limitation that is not accounted for in the CERQual confidence assessment is dissemination bias; when included studies are systematically unrepresentative of the complete body of research (65). This can occur when dissenting evidence or findings from studies are systematically made less accessible or available, and is a relevant consideration for qualitative or participatory research findings, which are often only partially or selectively disseminated, or sometimes not at all. Where possible, we have made considerations of these factors that may influence the confidence in our review findings. Furthermore, while the iterative process of evidence assessment enabled a critical interrogation of our findings, there remains an element of subjectivity in the overall confidence judgements. Similar challenges exist for the uncertainty assessment process in the IPCC, in which the calibrated language used to characterize and communicate levels of confidence, or degrees of certainty, in findings has been criticised for being overly subjective and ambiguous (93,94). To facilitate transparency in our own confidence assessment, the complete metadata and evidence profiles along with explanations contributing to our assessment process have been made available as supplementary material (2).

Discussion

From the review, synthesis, and confidence assessment of integrated climate-health monitoring and surveillance literature, we found that the inclusion of diverse knowledge systems contributes to these systems through the collection of more representative data; the reduction of selection and source biases; the processing and interpretation of more comprehensive datasets; as well as immediate decision making and prioritization of key issues. Furthermore, the inclusion of diverse knowledge systems contributes to integrated climate-health MSS through the definition of meaningful problems; the collection of more responsive data; the reduction of scale dependent biases; the development of multi-scale policy; long-term future planning; as well as creating effective knowledge-information-action pathways. Lastly, the inclusion of diverse knowledge systems contributes to integrated climate-health MSS through the divergence and discordance of methodologies and evidence.

Equity of methodologies and evidences

There is a tendency in our own knowledge systems to prioritize or suppress preferential types of evidence. As was the case for many studies in this review (45,68,72,73,76,84,87), integrated MSS that cherry-pick components of IKS and LKS only when they are convenient to “integrate” and able to be corroborated by “accepted” or “standard” scientific methodologies and evidence (as per quality and outcome measures) go on to reproduce a fallacy of incomplete evidence. In doing this, scholars have argued that we run the risk of losing the original meaning created by and within the structures of these knowledge systems (29–31,34,95). By continuing to reference and explain local and Indigenous processes using the same methodologies and concepts taken from Western science, not only do we lose meaning, but we also delegitimize other ways of knowing, and even jeopardizing the opportunities of being able to work together; researchers, scientists, local and Indigenous communities (31). Battiste (2005; pp.2) clarifies that Indigenous knowledge, for example, is "far more than a binary opposite of Western knowledge"; rather it can be used to benchmark limitations of these methodologies and evidence and fill ethical and knowledge gaps present in one singular approach to understanding (35). Agrawal (1995) suggests that 'productive' engagement of diverse knowledge systems requires us to go beyond the dichotomy of pinning one against another and work towards greater autonomy of each knowledge producing system (i.e. recognizing the intimate links between knowledges and power)(95). Recognizing that each system brings with it a set of methodologies and produces evidence that in turn have their own biases is also fundamental (45).

Returning to how the inclusion of diverse knowledge systems contributes to integrated climate-health MSS, we choose to focus on the divergence and discordance of methodologies and evidence. Marin (2010) describes the "subjective, contextual nature" in which climatic changes and impacts are, and need to be, interpreted; including a different perspective than the standard estimations of meteorological measures (83). Different epistemological systems have different scales of interpretation, time, and space, and applying one to another threatens our ability to create meaningful MSS. Mustonen (2015) describes the challenge to scientist looking for general data and running the risk of ignoring evidence that is considered relevant and significant by different methodologies and perspectives (75). Perhaps, this divergence and discordances could be more insightful than when both knowledge systems agree or corroborate each other.

Patterns for just processes

Alongside these insights of what we stand to gain from the inclusion of diverse knowledge systems, let us critically entertain the possibility of what we stand to lose if these processes of inclusion are not equitable. Our findings indicate that the inclusion of diverse knowledge systems contribute to integrated climate-health MSS across multiple processes. Our analyses indicate areas, or practice gaps, where the inclusions and contributions of diverse knowledge systems to integrated climate-health MSS processes could be developed (Figure 5 and Table 5). For example, more attention needs to be placed on having local and Indigenous experts initiating and defining these MSS from the beginning; including problem definition and tool development. This is consistent with the literature emphasizing early involvement with initiation and development stage in community-based or led-climate and health monitoring research (15,23). Natcher (2007; pp. 114) argues that "a more equitable role for community members in the research process" is created during critical stages of initiation and design; in particular when developing research methodologies (30). A recent systematic review of Indigenous community participation and decision-making in climate-related studies found that community participation in all stages of research varied depending on who initiated the project; where research initiated with (in mutual agreement between outside researchers and Indigenous communities) or by Indigenous communities had higher levels of engagement and inclusion throughout the entire research process (36).

From inclusion to ownership

We cannot disregard the ethical implications that arise from engaging diverse knowledge systems; and that cut across all three MSS processes. Particularly in an Indigenous context, where an explicit emphasis on self-determination and relational accountability to human, and non-human, communities exists, we are reminded that ethical practice is more than just the extent of engagement, but also the consistency and quality of that engagement (36). Our findings indicate an ethical practice gap in the recognition and actualization of Indigenous and local autonomy, intellectual property rights, and data sovereignty in integrated MSS (Figure 5). This concerns recognizing the right that Indigenous and local peoples possess to govern how their knowledges are generated, organized, stored, and shared; as well as to maintain, control, protect, and develop their intellectual property over these knowledges (29,34,95–97). There is intrinsic value that knowledge systems create for their own knowledge holders; far outside of the added-value to scientific research approaches, aims, and activities (34). Unfortunately, a majority of climate-related studies that access IKS and LKS still employ an extractive model of practice when engaging with Indigenous and local communities (36). This is where outside researchers use knowledge systems with knowledge holders and communities having minimal participation or decision-making authority. Despite IKS and LKS being recognized for their importance in climate-health monitoring and response and climate-related research, experts in these fields note that many studies still lack participatory design and substantial evidence to demonstrate community engagement and participatory processes in practice (23,36,47). Whether it be for the purposes of integrating climate-health MSS or otherwise, researchers and scientists need to recognize and uphold the different bodies that protect the knowledge, intellect, and well-being of Indigenous and local communities; just as we respect, and expect others to as well, our own ethical bodies.

Conclusion

The value of our findings and this review demonstrate how neither scientific, Indigenous, nor local knowledge systems alone will be able to contribute the breadth and depth of information necessary to detect, attribute, and inform action along these pathways of climate-health impact. If we are to advance our understanding of how and to what extent climate change is affecting health, then the inclusion of diverse knowledge systems is paramount. Bates (2007) demonstrates that by exploring "contrasting views" and an "apparent impasse" of Indigenous and Western scientific knowledges we begin to focus on practical realities of limitations and actionable solutions (31). One way is “to see from one eye with the strengths of Indigenous ways of knowing, and to see from the other eye with the strengths of Western ways of knowing, and to use both of these eyes together” (98)(pp. 335). This is referred to as ‘Two-Eyed Seeing’ and is being employed by many Indigenous scholars as a practical way of framing and navigating this integration of diverse knowledge systems; giving equity to evidences and methodologies (99).

As argued by Danielsen et al. (2008), for example, the contributions of multiple and diverse knowledge systems must be substantive and meaningful in order to add value to decision-making (100). This includes recognition that different knowledge systems reflect more than useful data or placeholders to corroborate or substitute favoured sources; the extent to which diverse sources and types of knowledges are integrated and favoured, or excluded, has important implications for prioritization of diverse perspectives, value judgements, and ultimately outcomes. Often, the contributions of diverse knowledge systems depends on the acceptance of them by the relevant scientific, policy, and practice communities (101); as much as the acceptance of science by Indigenous and local knowledge holders. While there is evidence emerging from studies in this review (69,75,79,82) and others in this field (36) to consider the intrinsic value and contributions of different knowledge systems as standalone contributors with value given by and for communities themselves (34).

As Marin (2010) and Danielsen et al. (2010) reiterate, the inclusion of diverse knowledge systems is not an isolated exercise of validating one system against the other to the benefit of removed stakeholders and outsiders. We argue that for improving integrated climate-health MSS the ethics for involving IKS and LKS is no different, and stems from ensuring the equity of diverse forms of evidence and methodologies, as well as a just process of inclusion throughout. *What* knowledges are considered legitimate and *how* knowledges are integrated reflect fundamental yet under-examined aspects of MSS detection, attribution, and action processes. Given the recognized value of local and Indigenous communities and knowledge systems for understanding and addressing the impacts of climate on health (23,29–33). The values and contributions of diverse knowledge systems is of particular significance as we consider the needs and challenges of integrating climate-health information and producing new knowledge and understanding. Should we begin to address these needs and challenges together, the gains in the quality and ethics of our information and systems is certain. Just as the gaps in knowledge that we trade off, should we continue to develop our information and understanding separately.

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Data Availability Statement

Any data that support the findings of this study are included within the article. See supplementary materials (1,2).

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