Introduction

In Northern Canada, the environment is undergoing various changes, stemming from climate change as well as resource extraction and development, which impacts often-intense socio-cultural stressors and transitions in the region (eg lack of adequate housing, food security challenges, mental health concerns, shifting cultural practices, increasing reliance on a wage economy, etc.). These changing environmental conditions present many challenges to health, with the most acute impacts identified among Inuit populations reliant on the land for sustenance and livelihoods [1–6]. Indeed, Inuit across Inuit Nunangat in Canada, and throughout the Circumpolar North, are indicating that observed changes in weather, climate and environment directly impact numerous facets of health and wellbeing, interacting with social determinants of health in a number of ways [1–6]. For example, early research indicates that these environmental stressors are already resulting in increased negative impacts on physical and mental health issues across the North [1–10]. While research has uncovered many associations between changing environments and health outcomes [1–6,10–30], detecting environment-health outcomes early and responding to them is an enormous challenge [31,45]. The need for comprehensive, sustainable, locally appropriate and integrated environment-health monitoring systems ¹ is, then, a major priority in this region [33–35,45].

In the global environment-health literature, the implementation of health monitoring and response is one of the most commonly identified health-related
climate change adaptation strategies [7,9,10,34,36–54,56–62]. Important health outcomes to monitor associated with a changing environment include physical outcomes, such as: rates of foodborne, waterborne and vectorborne diseases; incidence of injury or mortality due to hazardous travel conditions; and changes to nutritional intake as a result of increased reliance on retail food. There are also mental health outcomes, such as: wide-ranging emotional responses, increased rates of anxiety, depression, loss of identity and sense of place and interpersonal conflict [1–10]. As such, there is a repeated call for the creation of integrated environment-health-monitoring that uses novel approaches, integrates new types of data and includes multiple knowledge systems (eg Western Knowledge, Indigenous Knowledge, etc.) [7,9,10,34,36–54,56–62]. This is particularly important for Indigenous communities, who are often inadequately engaged in monitoring programmes [63–65]. Although public health monitoring is strong in many Circumpolar nations, there is a continued need to adequately use Indigenous Knowledge in these programmes in a meaningful way; failure to do so has led to various gaps and challenges in coverage, data quality and relevance [4,10–12,21,26,27,29–31,65].

Despite identifying integrated environment-health monitoring as a key environmental health priority, as well as international efforts towards mobilising integrated environment-health monitoring strategies [70,71], there has been very little research conducted on this topic in the Circumpolar North. Timely and reliable health information, government policies and response and local knowledge are not often integrated; yet, environmental change cannot be adequately responded to at local and regional levels without integrating numerous sources of information, focusing on multiple stressors and geographic coverage and using different knowledge systems, to produce real-time, usable data – data that can inform Northern policy, programming and decision-making.

Community-based monitoring (CBM) has been defined as a process in which different actors in a community – including local community members, governments, industry, community groups and academics – work together to observe and record common community concerns [35,72]. As opposed to top-town monitoring programmes in which monitoring happens in different communities, CBM works with local communities often relying on community knowledge in the design, development and implementation of monitoring initiatives. This type of monitoring is increasing in prevalence in Arctic and Subarctic regions of North America and Europe, specifically within Indigenous communities [35]. CBM is purported as a way of empowering communities, fostering self-determination, creating social capital, developing research skills among local people and strengthening partnerships between community members, researchers, government agencies and other like-minded institutions [35].

Considering this new and growing area of work, we conducted a review of environment-health monitoring programmes using information and communication technologies (eg tech-based platforms, software, mobile applications, etc.) in the Circumpolar North. An environmental scanning approach was used to provide a “snapshot” of the existing environment-health monitoring programmes during the review time period (September-December 2017) and identify areas of strength and areas of improvement [73]. This review aimed to discover, analyse and categorise programmes that: monitored climate change through observing and recording environmental change and/or human health indicators; took place in and around Indigenous communities; and had some level of community involvement. Additionally, this review examined the way monitoring programmes were using technology in the data collection and data sharing processes of their initiatives. This article details findings from this environmental scan review, and discusses: (1) gaps in integrated community-led climate change and health monitoring programmes; and (2) how innovative technology may enable real-time monitoring and the dissemination of information in communities. This synthesis is intended to support the development of further environment-health monitoring programmes in the Circumpolar North, which can inform and enhance decision-making, health programming and health adaptation to climate change and other environmental stressors.

Methods
To identify environment-health monitoring programmes that worked with Indigenous communities and used some form of technology (eg tech-based platforms, software, mobile applications, etc.), a review of community-based monitoring in the Circumpolar North was conducted using an

\[2\] For examples of public health surveillance see: The Arctic Climate Impact Assessment; The Alaska Surveillance, Epidemiology and End Results; and The International Circumpolar Surveillance System of Infectious Diseases.

\[3\] To help document existing programmes, The Atlas of Community-Based Monitoring and Indigenous Knowledge in a Changing Arctic – a website featuring many CBM programmes throughout the Circumpolar North – was established, providing many examples of CBM initiatives.
environmental scanning approach to systematically identify and consolidate information from a variety of sources [73]. An environmental scanning approach is often used in the context of needs assessments and health programming, and can be implemented to explore and contextualise specific environments and identify areas in need of improvement [73, 74]. Environmental scans have been used by other researchers in the Circumpolar North [75–79], and are recognised as a responsive and cost-effective tool for public health research [73]. This approach involves examining multiple sources of data (e.g., reviews of unpublished reports, consultation with community leaders, surveys, analysis of publicly available information, targeted internet searches of known programmes, peer-reviewed literature, etc.), and can target different populations, subjects or types of knowledge [73, 74, 76]. Owing to this flexibility, responsiveness and adaptability, there is no determined overarching framework for environmental scans; however, a common outcome of this approach is the ability to identify areas in need of improvement within a specific community or region based on available information [73]. As CBM in the Circumpolar North continues to expand, this approach proved useful in this review of existing programmes in the region.

**Identifying monitoring programmes**

To understand the existing environment of monitoring in the Circumpolar North, this review focused on programmes that were conducting, implementing or developing monitoring initiatives actively during Fall 2017 (September-December) and met the following criterion: (1) monitored environmental and/or human health indicators linked to climate change; (2) took place in and around Indigenous communities, and had some level of community involvement; (3) used some element of technology (e.g., mobile-phone, web-based technology, etc.); and (4) took place in the Circumpolar North.

Identification and classification of programmes involved several strategies, similar to the approach outlined by Mews et al. [76], in which data were collected through secondary sources such as consulting with relevant stakeholders, targeted internet searches and reviewing grey and peer-reviewed literature. Specifically, this environmental scan involved the following four strategies to identify programmes that met the above criterion:

1. **Consultation with academic researchers working on community-led monitoring in the North during September-December 2017**: In public health research, consultations have been used in the search phase of reviews to help develop key search terms, and identify relevant resources, as well as to validate and augment review findings, providing a more nuanced, robust and useful understanding of collected data [80, 81]. In this study, this method involved informal discussions with researchers to catalogue existing monitoring programmes in the North, as well as attending two workshops on community-based monitoring (The Community Based Monitoring Experience and Exchange Workshop, December 2017; and The Community-Based Climate Change/Environmental Monitoring Workshop, February 2018), with participants from Northern Canada and the USA. These consultations provided information regarding monitoring programmes to include in the study, as well as resources to help identify other programmes.

2. **Online searches of grey literature**: Between September to December 2017 grey literature was searched, including: project, research, and annual reports; conference proceedings; news articles; working papers; and webpages related to CBM programmes that fit the outlined criterion. Grey literature was searched using Google as the main search engine. Search terms used included combinations of words such as: community-based monitoring, Indigenous communities and web technology (Table 1). Additionally, programmes were identified through the Atlas of Community-Based Monitoring and Indigenous Knowledge in a Changing Arctic.

3. **Additional grey-literature search for mobile-phone applications**: Owing to the dearth of monitoring programmes using mobile applications throughout the Circumpolar North, a secondary grey-literature search for global monitoring mobile applications was conducted, using Google as the primary search engine. This secondary grey-literature search provided broader data from which to draw key insights and lessons regarding mobile application use in the context of environment-health monitoring.

4. **Systematic scoping review of peer-reviewed articles**: A systematic scoping review of the peer-reviewed literature was conducted [82, 83]. This involved developing a search string, with the guidance of a research librarian, to search MEDLINE® and Web of Science™ (Appendix 1) to identify potentially relevant citations. The search was conducted in July 2015 and then again in June 2017. A hand search of three key journals (International Journal of Circumpolar Health, Arctic, and Environmental...
Table 1. Search term combinations used to identify community-based monitoring programmes in the Circumpolar North: One term per criterion column was combined in each Internet search*.

| Search Term                  | Criterion One | Criterion Two | Criterion Three | Criterion Four |
|------------------------------|---------------|---------------|-----------------|----------------|
| Community-based* monitoring  | Indigenous Knowledge | Mobile app* technology | Circumpolar North |
| Environment* monitoring      | Indigenous communities | Web* technology | Arctic |
| Health monitoring            | Indigenous    | Smartphone | Polar regions |
| Monitoring climate change*   | Inuit         | Technology  | North |
| Monitoring environmental* change | First Nations |               |               |

*an asterisk indicates that a variation of the word may have been used

*Health Perspectives* was performed in June 2017. Citations were uploaded into Mendeley® and de-duplicated, and then uploaded into Distiller software®. Using Distiller®, a two-stage screening process was conducted to identify relevant articles. First, two independent reviewers screened the titles and abstracts of each citation for relevance; potentially relevant citations proceeded to the second stage, where the full-text of the article was screened for relevance again by two independent reviewers. Inclusion criteria were identified a priori, and articles were included if they: were published in English between 2000–2016; were a primary or secondary study; were conducted in the Arctic or Subarctic; involved some form of environmental monitoring; and included some form of human health monitoring. A secondary screening was then conducted of the eligible articles, searching for CBM programmes that used technology to collect, share or visualise data; articles that met this criterion were then included in this study (Figure 1). The level of agreement between the two independent reviewers was measured using Cohen’s Kappa (κ). Conflicts between reviewers were discussed and reconciled regularly throughout the review process.

(5) **Additional peer-reviewed literature search for specific monitoring programme:** To supplement the formal systematic scoping review, an additional search of peer-reviewed literature was used to find out more information about programmes identified from the grey literature review and to identify additional monitoring programmes that were active from September-December 2017. To conduct this search, each programme name identified through the grey literature review was used as a search term to search Primo Central™ – a search engine of online databases – for associated peer-reviewed articles, with no date restrictions on the search. This method allowed for greater insight and context into the various monitoring programmes, such as details on the methods used to select indicators.

**Data analysis**

Once relevant community-based or community-led monitoring programmes were identified, key information was extracted about the programmes, categorised and characterised to create a database using Microsoft Excel [84]. Key attributes for each programme were recorded in this database, including: region and geographic location; lead organisation; partner organisations; programme goals; level of community involvement, engagement or leadership; key indicators monitored; the methods used to develop the included indicators; information regarding how data were collected, monitored and stored through the programme; and how technology, including both mobile applications and web-based tools, were utilised. Additionally, key quotations found on programmes’ websites, in reports and/or publications describing the relevant monitoring programmes were recorded, sorted and thematically analysed to contextualise the information included in the database [84].

After the initial categorisation and characterisation were complete, data were analysed qualitatively through an iterative and constant comparative approach [85,86]. First, a preliminary analysis of each programme was conducted using the information recorded in the database, coding the data for emergent themes categorised by content, approach, methods utilised, outputs and key findings. Based on this thematic analysis, preliminary themes were identified for each programme attribute. A detailed analysis was then conducted, constantly comparing and contrasting programmes to look for similarities and differences, and to define key features, strategies, lessons learned, recommendations and outcomes across the various programmes [85].

To analyse the types of data recorded by monitoring programmes, the indicators monitored (eg water quality, etc.) were listed in a separate database, and divided into emergent categories (eg aquatic, etc.). The frequency of an indicator across monitoring programmes and the number of indicators for each programme were recorded, as well as the most common indicators in each category, and any categories for which indicators were underrepresented or not accounted.
Results

In total, 18 monitoring programmes that fit the established criterion in the Circumpolar North were identified from the peer-reviewed and grey-literature searches, and an additional three global app-based climate monitoring programmes were identified and included for further depth (Table 2 and 3). Additionally, 74 distinct indicators/categories were identified and analysed (Table 4–6).

Nine overarching categories developed through the qualitative analysis of these indicators, including: atmosphere, aquatic environment, cryosphere, marine ecology, wildlife ecology, plant ecology, contaminants and human and built environment. The qualitative analysis revealed three key themes: community involvement, indicators chosen for monitoring and use of technology, such as app-based platforms.

Figure 1. Diagram depicting the flow of identification, screening and eligibility assessment of articles included in this review (n = 3).
Table 2. Identified environment-health monitoring programmes in the Circumpolar North that had some level of involvement with Indigenous communities and used some form of information or communication technology.

| Monitoring Programme* | Geographic Region | Associated Organizations |
|-----------------------|-------------------|--------------------------|
| Arctic Borderlands Ecological Knowledge Society (ABEKS) | Porcupine Caribou Herd area and Mackenzie Delta area in Northwest Territories (NWT), Yukon, and Alaska | ABEKS Directors, participants and partners are from Gwich’in and Inuvialuit organizations, governments and are scientists, and community residents |
| Arctic Monitoring and Assessment Programme (AMAP) | Arctic Wide | Arctic Council |
| Avatitiv Program | Nunavik | Centre d’études Nordiques – Université Laval |
| Circumpolar Biodiversity Monitoring Programme (CBMP) | Circumpolar North | Conservation of Arctic Flora and Fauna (Arctic Council) |
| Community-Based Water Quality Program (CBWQP) | Northwest Territories Wide | Mackenzie DataStream, NWT Discovery Portal, Government of NWT |
| Community-Based Wildlife Monitoring Network (CBWMN) | Nunavut Settlement Area | Nunavut Wildlife Management Board |
| Community Ecological Monitoring Program (CEMP) | Yukon Boreal Forest – Klune Lake, Mayo, Faro, Watson Lake, and Whitehorse | Arctic Institute Research Station at Klune Lake, Environment Yukon, the Canadian Wildlife Services and Yukon College |
| Community Observing Network for Adaptation and Security (CONAS) | Across the Bering Sea in both Alaska and the Russian Far East | Universities of Alaska and Idaho, the Aleut International Association, local community and regional governments in the U. S. and Russia |
| eNuk Program*** (eNuk) | Rigolet, Nunatsiavut | The Rigolet Inuit Community Government, the University of Guelph, the Labrador Institute of Memorial University, the University of Alberta, Nunatsiavut Government |
| Inuit Siku Atlas | Baffin Island Nunavut – Cape Dorset, Clyde River, Igloolik, and Pangnirtung | Inuit Sea Ice Use and Occupancy Project |
| Inuvialuit Settlement Region Community-Based Monitoring Program (ISR-CBMP) | Inuvialuit Settlement Region | ISR Hunters and Trappers Committees, ISR Wildlife Co-Management Boards, Inuvialuit Game Council, the Inuvialuit Regional Corporation, & the Joint Secretariat |
| Marian Watershed Stewardship Program (MWS) | Tlicho First Nation in the Northwest Territories | Tlicho Government, Wek’eexhii Land and Water Board and Wilfred Laurier University |
| Northern Contaminants Program (NCP) | Northern Canada | Aboriginal Affairs & Northern Development Canada |
| Nunavut Community Aquatic Monitoring Program (NCAMP) | Nunavut Wide | Fisheries and Sealing Division of the Government of Nunavut |
| PISUNA-net (PISUNA) | Greenland | The Greenland Government, Local Resource Councils, Exchange for Local Observations and Knowledge of the Arctic (ELOKA) |
| Seasonal Ice Zone Observing Network (SIZONet) | Bering and Chukchi Sea | University of Alaska Fairbanks, Sea-Ice System Services, ELOKA |
| SIKU** | Eastern Hudson Bay region of Nunavut and Quebec’s Nunavik region | The Arctic Eider Society |
| SmartICE** | Nain, St. John’s and Pond Inlet | Memorial University, Nunatsiavut Government, Nain Research Centre |

Table 3. Identified global climate change monitoring mobile-phone applications.

| Global app-based climate monitoring programmes | Geographic region | Associated organizations |
|---------------------------------------------|-------------------|--------------------------|
| Globe Observer App | Worldwide | National Aeronautics and Space Administration (NASA) |
| ISeeChange Tracker | Worldwide | NASA’s Orbiting Carbon Observatory Mission, National Oceanic and Atmospheric Administration, Community Collaborative Rain, Hail and Snow Network, and more |
| Local Environmental Observations Network (LEO) | Worldwide | Alaska Native Tribal Health Consortium and Resource Data Inc. |

* The monitoring programmes listed are limited to those found during searches performed in English.
** Currently developing or testing mobile-phone applications
*** The indicators used in the eNuk Program are currently being developed in a participatory fashion, in interviews with community members conducted by community researchers; as a result, they were not included in the database designed to analyse indicators

Indicators used to monitor change and how they were used

There were 74 indicators monitored across the different programmes, with the number of indicators/categories monitored by each programme varied. SmartIce monitored the smallest number of indicators, exclusively monitoring sea-ice thickness, while the LEO Network monitored the greatest number, allowing participants to record observations related to approximately 24 different categories of environment/human change. The mean number of indicators collected was nine while the majority of programmes (n = 13) monitored five or fewer indicators/categories.

According to the available data, the different monitoring programmes selected indicators in a variety of ways. Methods for indicator development included:
### Table 4. The environment and health indicators captured in monitoring programmes in the Circumpolar North*

| Monitoring Programs | Categories of Indicators Monitored |
|---------------------|-----------------------------------|
|                     | ATMOSPHERIC | AQUATIC | CRYOSPHERIC |
|                     | Carbon balance in tundra | air temperature | precipitation increase/decrease, change in seasons |
|                     | Snow thickness/depth/duration | Precipitation increase/decrease, change in seasons | Extreme weather conditions (drought, heatwaves) |
|                     | Temperature | Air quality (smog/pollution) | Air quality (smog/pollution) |
|                     | Snow thickness/depth/duration | Snow thickness/depth/duration | Snow thickness/depth/duration |
|                     | Precipitation increase/decrease, change in seasons | Precipitation increase/decrease, change in seasons | Precipitation increase/decrease, change in seasons |
|                     | Extreme weather conditions (drought, heatwaves) | Extreme weather conditions (drought, heatwaves) | Extreme weather conditions (drought, heatwaves) |
|                     | Clouds | Ice formation | Ice formation |
|                     | Ice thickness | Ice formation | Ice formation |
|                     | Ice edge location | Ice formation | Ice formation |
|                     | Sea-ice extent | Ice formation | Ice formation |
|                     | Sea-ice velocity | Ice formation | Ice formation |
|                     | Presence of moving ice | Ice formation | Ice formation |

* The monitoring programs listed are limited to those found in searches performed in English.
Table 5. The environment and health indicators captured in monitoring programmes in the Circumpolar North.

| Monitoring Programs                                      | MARINE | WILDLIFE ECOLOGY | PLANT ECOLOGY |
|----------------------------------------------------------|--------|-----------------|---------------|
|                                                          | Indicators Monitored | Indicators Monitored | Indicators Monitored |
| Arctic Borderlands Ecological Knowledge Society          |        |                 |               |
| Arctic Monitoring and Assessment Program                 |        |                 |               |
| Avativut Project                                         |        |                 |               |
| Circumpolar Biodiversity Monitoring Program              |        |                 |               |
| Inuvialuit Settlement Region Community Based Monitoring Program |        |                 |               |
| Community Based Monitoring Program                       |        |                 |               |
| Community Based Water Quality Program                   |        |                 |               |
| Community Based Wildlife Monitoring Network              |        |                 |               |
| Community Ecological Monitoring Program                  |        |                 |               |
| Community Observing Network for Adaptation and Security  |        |                 |               |
| Globe Observer                                           |        |                 |               |
| Inuit Siku Atlas                                         |        |                 |               |
| ISeeChange Tracker                                       |        |                 |               |
| Local Environmental Observations Network Tracker         |        |                 |               |
| Marian Watershed Stewardship Program                     |        |                 |               |
| Northern Contaminants Program                            |        |                 |               |
| Nunavut Community Aquatic Monitoring Program             |        |                 |               |
| PISUNA Net                                               |        |                 |               |
| Seasonal Ice Zone Observing Network                      |        |                 |               |
| SIKU SmartICE                                            |        |                 |               |

Frequency of Indicator: 7 2 1 4 2 9 1 3 4 5 9 2 3 1 1 4 2 1 1 3 1

* The monitoring programs listed are limited to those found in searches performed in English.
Table 6. The environment and health indicators captured in monitoring programmes in the Circumpolar North.

| Monitoring Programs | Categories of Indicators Monitored |
|---------------------|-----------------------------------|
|                     | LAND                              |
|                     | HUMAN/BUILT ENVIRONMENT            |
|                     | CONTAMINANT                        |
|                     | Indicators Monitored              |
|                     |                                    |
| Arctic Borderlands Ecological Knowledge Society |                     |
| Arctic Monitoring and Assessment Program |                     |
| Avativut Project |                     |
| Circumpolar Biodiversity Monitoring Program |                     |
| Inuvialuit Settlement Region Community Based Monitoring Program |                     |
| Community Based Water Quality Program |                     |
| Community Based Wildlife Monitoring Network |                     |
| Community Ecological Monitoring Program |                     |
| Community Observing Network for Adaptation and Security |                     |
| Globe Observer |                     |
| Inuit Siku Atlas |                     |
| ISeeChange Tracker |                     |
| Local Environmental Observations Network Tracker |                     |
| Marian Watershed Stewardship Program |                     |
| Northern Contaminants Program |                     |
| Nunavut Community Aquatic Monitoring Program |                     |
| PISUNA Net |                     |
| Seasonal Ice Zone Observing Network |                     |
| SIKU |                     |
| SmartICE |                     |
|                     | Frequency of Indicator             |
|                     | 1 1 1 4 1 3 1 2 5 1 1 1 1 1 1 1 1 3 2 2 1 1 2 3 |

* The monitoring programs listed are limited to those found in searches performed in English.
consultation involving international and regional workshops (e.g., ABEKS, CBMP, PISUNA); the development of a peer-reviewed indicator strategy (e.g., CBMP); co-developed surveys and questionnaires (e.g., CONAS); discussions with natural resource councils (e.g., PISUNA); semi-structured interviews and interactive community events with community members (e.g., eNuk); examining regional priorities (e.g., CBMP, ISR CBMP); decision-making by programme staff (e.g., Globe Observer, ISeeChange); and indicators suggested by those collecting data (e.g., eNuk, ISeeChange, LEO Network, PISUNA). Although these various methods provided insight into the processes some programmes used to select indicators, the majority of programmes (n = 13) did not explicitly state how indicators were selected, based on the identified grey and peer-reviewed literature.

Of the 74 identified indicators/categories (Table 4), the most commonly monitored were: ice thickness, wildlife distribution, wildlife abundance/population, changing fish distribution, change in water level/flooding, change in wildlife migration, consumption/harvest of traditional food, sea-ice extent, timing of ice freeze-up/break-up, snow depth/duration and air temperature (Figure 2). Many of the monitoring programmes explicitly monitored indicators associated with different and changing seasons (e.g., timing of ice freeze-up/break-up); however, not all monitoring programmes explicitly stated whether or not monitoring occurred year-round.

The majority of monitoring programmes with specified indicators focused exclusively on environmental change, with only seven out of 20 (35%) focusing on the impacts of climate change on human health: The Arctic Borderlands Ecological Knowledge Society; Arctic Monitoring and Assessment Programme; Circumpolar Biodiversity Monitoring Programme; Community-Based Wildlife Monitoring Network; Inuvialuit Settlement Region Community Based Monitoring Program; ISeeChange; and the LEO Network. The Arctic Monitoring and Assessment Programme monitored the greatest number of indicators related to human health (n = 4), including: consumption/harvest of traditional food, common causes of death, infant mortality and contaminants in humans. The remaining three Circumpolar programmes monitored consumption/harvest of traditional food as the sole indicator of human health, while the two global monitoring apps allowed users to input any observations related to human health. Notably, mental wellness was not explicitly monitored in any of the listed indicators; however, the eNuk Program, whose indicators were not yet published at the time of this review, was conceptualised as an integrated environment-health monitoring programme with the goal of monitoring a range of environmental conditions and both physical and mental health indicators.

There were a number of reported outcomes and outputs from these monitoring programmes. First, several of the organisations reported using the data to inform community, regional, and national decision-making (e.g., CBWMN, CONAS, ISR CBMP, NCP, PISUNA and SmartICE). For example, data collected through PISUNA were submitted to local authorities and central governments to take action and inform regional management decisions, such as changes to harvesting seasons, quotas and local laws and bylaws related to fishing methods and equipment [87]. Second, programmes reported using the information to develop tools for data sharing, education, and skill development (e.g., Avativut, ISR CBMP, Inuit Siku

Figure 2. Indicators commonly monitored by environment-health monitoring programmes in the Circumpolar North and global climate change monitoring mobile applications.
Atlas, PISUNA, SIZONet and SmartICE). These tools included interactive maps, databases and archives, online resources for harvesters and interactive multimedia outputs such as audio, video and photographs of observations and educational resources for Northern schools (eg CBMP; Inuit Siku Atlas; ISR PISUNA and SIZONet). Finally, these programmes reported producing community, regional, national and/or international publications, reports and press releases to communicate the results of their programmes at various scales (eg AMAP, CBMP, CEMP and CONAS). Through these different outcomes and outputs, it was evident that these monitoring programmes have the potential to further understandings of the impacts of climate change throughout the Circumpolar North.

Community involvement

Although all of the monitoring programmes analysed reported some level of community involvement, the degree to which community members were involved in monitoring efforts varied, and few community-led monitoring programmes were identified. Programmes ranged from being developed and implemented by community members (eg eNuk, ISR-CBMP and PISUNA), to outside organisations consulting with community members (eg SmartICE, and NCAMP), to community members involved in the data collection phases of programmes (eg CBWMN and CEMP). Of the 21 monitoring programmes analysed, less than a quarter were classified as community-led (n = 5). The remaining programmes either partnered with communities (n = 6) or engaged with communities in another way (n = 7) (eg consultation or data collection).

In programmes identified as community-led or community-based, community members played a key role in determining what indicators should be monitored. For example, on PISUNA’s website, they explained the process used for determining what would be monitored, stating: “Local Resource Councils, established at the community level and comprising hunters, fishers and other individuals with an interest in the environment, decide what will be monitored based on the relevance for their community” [87]. The Marian Watershed Stewardship Program, another community-led programme, discussed taking a similar approach to determining what to monitor, explaining, “[Our program] is a community-based monitoring program that is being developed based on the questions and needs of the Tlicho people” [88].

Although involving community members in monitoring is an integral part of CBM, aside from the three global-monitoring apps – which allowed anyone who had access to a mobile-phone to collect data – the majority of programmes were not open to the public and dedicated monitors were selected. These monitors often included: harvesters (ie hunters and fishers) (eg CBWMN, CONAS, ISR-CBMP, PISUNA and SIKU); Elders (eg CONAS); local experts (ie sea ice and wildlife experts) (eg ABEKS and SIZONet); and trained community members (eg CBWMN, CONAS and MWSP).

Use of technology

All of the programmes included in this review used some form of web-based technologies to: visualise, analyse, store and share data that were collected (n = 12); promote the programme via a webpage (n = 21); and collect data (n = 6). For example, The Inuit Siku Atlas had an online platform that allowed stories and data to be shared in the form of maps, audio, video, picture and text across Nunavut and beyond, allowing for information to be more easily accessed and updated [89]. PISUNA also had a web-based application, where the observations made by local communities were stored, publicly available and searchable [87]. Similarly, the Avativut Program had a web portal, which allowed data to be inputted, accessed and archived [90]. The Avativut portal also enabled consultation of scientific protocols, sharing video clips and photographs and communication across data collection locations [90].

The results of this environmental scan indicated that, in large part, advanced web-based technology, such as mobile-phone applications, or tablets, were not used in the data collection process of most monitoring programmes in the Circumpolar North (n = 3/18). For example, data collectors for the Community-Based Wildlife Monitoring Network used hand-held computers to record their observations when out on the land; once they returned home trained data clerks transferred information from the hand-held devices to a regional database [91]. In other monitoring programmes, data were collected using hand written notes, or through paper surveys.

This research identified only three programmes in the Circumpolar North that were developing apps for community-based monitoring in the region at the time of this study. The first programme, SmartICE, was designed to observe and disseminate knowledge on sea-ice (ie thickness and surface characteristics), and was developing a mobile-phone application to provide the most up-to-date sea-ice information to community members and to allow for the recording of observations by people travelling on the sea-ice [92]. The second programme, SIKU, focused on monitoring ice conditions
and wildlife and was developing an app and associated web-based tools with the goal of helping to facilitate knowledge transfer, sea-ice safety, participatory mapping, language preservation, education, training and environmental stewardship [93]. The third, and final programme, eNuk, was developing the eNuk app to allow community members to record and respond to both environment and/or health indicators of climate change via online posts, photos or video uploads. As mentioned, internationally, this research identified three additional monitoring programmes that used app-based technologies to track environmental change: Globe Observer, iSeeChange and LEO Network. These programmes allowed individuals to document different changes they saw in their everyday lives through an app platform, and consolidate these observations and inputs into aggregate information centres. There are therefore many opportunities to incorporate new technologies and innovations into environment-health monitoring systems in the Circumpolar North.

This research found that internet and cellular phone connectivity was often limited or non-existent in the North, which has the potential to negatively impact the timeliness of these mobile-phone applications. These app-based monitoring programmes were exploring new and innovative ways to address these concerns. An example of a programme attempting to bridge this digital divide is the SmartICE programme. SmartICE used stationary sensors (SmartBUOYs) to provide timely information about sea ice to community members via satellites, as well as through a mobile, sled-based technology pulled by snowmobiles (SmartQAMUTIK) to measure sea ice thickness [94]. This information was gathered by community researchers and shared through a cloud-based interface, the SmartICE App itself, and paper reports [94]. This example shows how innovative technology can be used to meet the unique context of environmental-health monitoring in the North.

**Discussion**

As evidenced by this research and outlined in the literature [35], Indigenous communities across the North are increasingly involved in the design, development and implementation of monitoring programmes in order to observe, record, and respond to climate change. As this synthesis indicates, several important opportunities exist with regard to Indigenous communities monitoring the health effects of climate change, including the need for programmes to: (1) be community-led and community-based; (2) holistically incorporate health and environment; and (3) make use of innovative technologies that are locally appropriate and usable.

In many Indigenous communities across the North, environment-health monitoring programmes that engage community members have been identified as being more successful than other programmes [95]. Specifically, these programmes are recognised in the literature for their ability to combine cultural knowledge surrounding environmental changes with environmental observations, leading to important community adaptation and emergency response strategies [96]. This research found that although Indigenous communities were increasingly involved in the monitoring of environment and health through community-based and community-led monitoring, the extent of community involvement varied and was often limited. Although research has identified the benefits of CBM for Indigenous communities, the data analysed in this environmental scan were not sufficient to determine the success of community-led versus community-based monitoring programmes. More research is needed to determine the relative effectiveness of increased community involvement in monitoring initiatives.

Analysing the indicators used by monitoring programmes provided insight into what indicators were used to monitor climate change within the North. Although climate change is recognised as having numerous effects on health and wellbeing [1–10], this research discovered that few monitoring programmes integrated both environment and health indicators in their programmes in a holistic way. The lack of integration between environmental and health indicators may point to a lack of integration between environmental and health monitoring more broadly, which is particularly problematic for Indigenous communities that conceptualise wellbeing as closely tied to the environment and land [10–12,21,27,30,65]. Additionally, the analysis of indicators revealed a paucity of community-based monitoring programmes focused on mental wellbeing, which should be addressed for many reasons, including the intimate connections between climate change and Indigenous mental wellbeing that have been identified by community members and researchers alike [2–6].

Existing literature on monitoring health impacts of climate change has highlighted challenges associated with collecting these health indicators, including: (1) identifying relevant health indicators is often dependent on a population’s vulnerability and adaptive capacity, as well as many other determinants; (2) accessing and analysing health data from multiple sources is difficult; (3) determining relationships between complex and often distal climate related risk factors and their health consequences is methodologically challenging;
and, (4) identifying, collecting and analysing health data for health practitioners, as well as local and regional governments requires resources and capacity [30,97–99]. These challenges may explain why environmental indicators associated with climate change were more frequently monitored than health indicators, and why there were no indicators of mental health monitored in the literature included in this review.

The way technology was used by the majority of identified monitoring programmes (ie data visualisation, storage and sharing) has potential to help organise and share information in a way that is accessible beyond research institutions. This research indicated, however, that important challenges remain for programmes with regard to using advanced technology in the data collection phases of monitoring programmes. Similar to existing research [35,95], the data revealed that programmes often used low-tech approaches to data collection as a result of poor bandwidth in higher latitudes and minimal computer access, leading to potentially problematic delays in reporting and data errors. As highlighted above, internet and cellular network connectivity issues in the North can often delay time-sensitive information recorded in mobile applications from being uploaded in real-time. Innovative solutions, such as the mobile phone application being developed by the eNuk programme, as well as the stationary and mobile sensors (SmartBOUYs and SmartQAMUTIK), and the satellite technology used by SmartICE [94] are beginning to address these challenges and bridge the technological gap that exists in many communities in the North.

This review revealed several limitations to existing community-based monitoring programmes in the Circumpolar North. Although the reviewed programmes all had some level of community involvement, only a few programmes were actually led by community members. Further, through examining the indicators monitored by these programmes, it was evident that there is a gap in monitoring the health implications of climate change for communities in this region. Finally, this research revealed that low-tech tools were often used to gather data and monitor indicators, and the need for innovative solutions to gathering this data and improving internet connectivity issues in the North.

Despite the information gleaned from this environmental scan and subsequent analysis, there were several limitations to this research. An environmental scan is designed to be an efficient way of providing a “snapshot” of existing monitoring programmes in the Circumpolar North rather than a comprehensive review [73]. The searches were conducted in English, which may have limited the majority of identified programmes to English-speaking regions of the Circumpolar North. Additionally, some CBM programmes may not have a presence on the internet, inadvertently excluding them from this study.

A challenge involved in categorising and analysing the indicators monitored by environment-health monitoring programmes, which is perhaps indicative of a greater challenge in monitoring, was that the indicators of environment and human health were often different for each programme. For example, some programmes stated that they monitored the broad category of “sea ice,” while others monitored more specific elements of sea ice including “thickness, colour, time of break-up, incidents of animal entrapment in sea ice, etc”. Although this information was useful as it revealed the types of indicators being monitored, it made comparability across programmes difficult.

**Conclusion**

This review indicated that there are many opportunities for growth within community-based monitoring in this region. Increased community leadership throughout the design and delivery of monitoring programmes has the potential to enable community prioritisation of needs in regional decision making, for the development of relevant indicators of change that reflect Indigenous connections between environment and wellbeing, and for the creation of locally and culturally useful technological innovation [100]. Supporting monitoring programmes in the North, which are community-led, integrated and make use of culturally appropriate technology, can help fill the gaps in existing programming outlined throughout this article, potentially leading to more robust and meaningful monitoring of health-related impacts of climate change in and across Indigenous communities in the Circumpolar North.

**Acknowledgments**

This work was supported by researchers from the University of Guelph, located on the ancestral and treaty lands of the Attawandaron people and Mississaugas of the Credit; the Labrador Institute, located on the lands of the Innu and Inuit of Labrador; and the University of Alberta, located on Treaty 6 territory, traditional lands of First Nations and Métis people. We would like to thank participants of the community-based monitoring workshops - which several of the authors attended - for their invaluable insight. We would also like to thank Dr. Mark Andrachuk for providing his suggestions of CBM programs and support throughout the writing of this paper. Additionally, we would like to acknowledge the anonymous reviewers for their incredibly valuable feedback.
Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Canadian Institutes of Health Research and Polar Knowledge Canada.

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## Appendices

Appendix 1. Finalized search strings for Web of Science™ and MEDLINE® aggregator databases to identify articles related to integrated surveillance strategies in Arctic and Subarctic regions of the Circumpolar North that involved considerations for the natural environment, human health, and surveillance (2005–2016).

| Component | Web of Science™ | MEDLINE® |
|-----------|----------------|----------|
| Natural environment component | (((climat* NEAR/2 (change or variabl* or extreme)) or global warm* or ice or disaster* or fire* or cyclon* or storm* or flood* or drought* or rain or snow or (tidal NEAR/2 wave*) or tornado* or (food NEAR/2 (suppl* or safe* or security or quality))) or (water NEAR/2 (suppl* or fresh or drink* or security or quality or pollut*)) or weather or (extreme NEAR/2 (cold or heat)) or (air NEAR/2 (quality or pollut*)) or humidity or temperature* or wind* or “ultraviolet rays” or (environment* NEAR/2 (monitor* or medicine or health or pollut* or exposure**)))) | (((climat* adj2 (change or variabl* or extreme)) or global warm* or ice or disaster* or fire* or cyclon* or storm* or flood* or drought* or rain or snow or (tidal adj2 wave*) or tornado* or (food adj2 (suppl* or safe* or security or quality))) or (water adj2 (suppl* or fresh or drink* or security or quality or pollut*)) or weather or (extreme adj2 (cold or heat)) or (air adj2 (quality or pollut*)) or humidity or temperature* or wind* or ultraviolet rays or (environment* adj2 (monitor* or medicine or health or pollut* or exposure**)))) |
| Surveillance component | (((ecological* NEAR/3 monitor*) or (disease NEAR/2 notification) or (surveillance or monitor* or track* or assess*) NEAR/3 (population or health* or environment*))) or (prevent* or warn* or prepar* or surveillance or monitor* or track* or assess* or detect*) NEAR/3 (sentinel or health*)) or (prevent* or warn* or prepar* or surveillance or monitor* or track* or assess* or detect*) NEAR/3 system*) or (strateg* NEAR/3 (climat* or environment* or adapt*)) | (((ecological* adj3 monitor*) or (disease adj2 notification) or (surveillance or monitor* or track* or assess*) adj3 (population or health* or environment*))) or (prevent* or warn* or prepar* or surveillance or monitor* or track* or assess* or detect*) adj3 (sentinel or health*)) or (prevent* or warn* or prepar* or surveillance or monitor* or track* or assess* or detect*) adj3 system*) or (strateg* adj3 (climat* or environment* or adapt*)) |
| Human health component | (((health or wellbeing OR safe* or injur* or illness* or disease* or infect* or “frost bite” or “burn” or “wound”))) | (((health or wellbeing OR safe* or injur* or illness* or disease* or infect* or “frost bite” or “burn” or “wound”))) |
| Geographic focus | (Circumpolar or polar or “arctic Canada” or Canada or Alberta or “British Columbia” or “New Brunswick” or Manitoba or “Newfoundland and Labrador” or “Northwest Territories” or “Nova Scotia” or Nunavut or “Prince Edward Island” or Ontario or Quebec or Saskatchewan or Yukon or Nunavik or Nunatsiavut or Inuvialuit or Norway or Svalbard or Greenland or Denmark or Alaska or USA or Russia or Sweden or Finland or Iceland or Scandinavia or “Nordic countr*” or Arctic or North*) | (Circumpolar or polar or arctic Canada or Canada or Alberta or British Columbia or Manitoba or Newfoundland and Labrador or Northwest Territories or Nunavut or Ontario or Quebec or Saskatchewan or Yukon or Nunavik or Nunatsiavut or Inuvialuit or Norway or Svalbard or Greenland or Denmark or Alaska or USA or Russia or Sweden or Finland or Iceland or Scandinavia or “Nordic countr*” or Arctic or North*).