Chapter 8

Collaborative Uses of Geospatial Technology to Support Climate Change Adaptation in Indigenous Communities of the Circumpolar North

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Additional information is available at the end of the chapter

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Abstract

A literature review is conducted of geospatial technologies in community-based research on ice and mobility among Indigenous people of the circumpolar north. Numerous studies explore the use of traditional knowledge in the Arctic on sea ice, but limited evidence of community-based research in sub-Arctic communities and in freshwater ice systems is found. Geographical Information Systems (GIS) and remote sensing tools have been applied in a variety of ways in support of community adaptations. These include the production of living memory maps, ice classification systems, and geodatabases that reflect the relationship-building nature of collaborations between Indigenous traditional knowledge holders and scientists. Satellite imagery—particularly synthetic aperture radar (SAR)—is widely used to characterize traditional understandings of ice to help tailor geospatial tools, climate research, and early warning systems, so that they may be used more effectively to address community interests and needs. As numerous mapping platforms have been developed in the circumpolar north, there are important considerations with respect to data management, Indigenous rights, and data sharing. We see opportunities for further research in lake and river ice, and in further developing early warning systems to address the growing problem of unpredictable ice regimes in Arctic and sub-Arctic regions.

Keywords: circumpolar north, climate change, ice, traditional knowledge, geospatial technologies

1. Introduction

The climate system of the circumpolar north is undergoing transformative change. Average annual Arctic air temperatures have increased by 2.9°C since the start of the twentieth century [1]. As a result, significant sea ice declines through most of the Arctic have occurred over the past 30 years [2], while inland, freshwater ice systems have experienced shorter seasons of ice cover due to a significantly later freeze-up and earlier breakup [3]. The decline in sea ice leads to greater absorption of solar radiation in the Arctic Ocean in early autumn, which intensifies vertical fluxes of heat and moisture into the atmosphere, amplifying the effects of climate change in poles to approximately twice the global average [4].

Such changes have affected the mobility of Indigenous people of the north, who rely on the frozen landscape to move freely during winter months [5, 6]. Sea ice, frozen lakes, and rivers act as virtual highways in the north, while seasonal winter ice roads are constructed to provide access to the north for various industries, and are crucial for bringing year-round essentials, such as food, fuel, construction, and household items into remote communities [7, 8]. In recent years, travel to hunting grounds is less predictable, and ice persists for shorter periods of time, posing hazards to hunters [7]. Beyond direct impacts to traditional land use, these changes impact the northern community's well-being in terms of food security, health, culture, and spiritual life [9].

Regional characterizations of Arctic ice systems, which bring together information from satellite imagery, in situ observations, and climate models, are being used to help better simulate global climate projections [10–12], to forecast seasonal sea ice extent [13], to map potential new Arctic shipping routes [14], and to explore opportunities for natural resources development [15]. However, at the local level, a variety of geospatial tools have emerged in polar research to support Indigenous communities adapting to climate change. This chapter looks at what geospatial technologies have been used in Arctic and sub-Arctic regions to support adaptations to changing ice regimes. We will explore what outputs have emerged from geospatial research collaborations, and what lessons have been learned. We will then look at more recent concerns of data management, and how this has led to the establishment of numerous networks and mapping platforms in the circumpolar north (see Section 2 for the criteria used to delimit the region).

Community-based cartography in the Arctic is not new. Early Inuit maps were made with ephemeral pieces of the landscape, as charts were drawn into snow and sand, and detailed coastal relief maps were carved or assembled from sticks and stones [16–18]. It is said that maps of winter trails are etched in the minds of those who make and use them [5]. The communication of this collective traditional knowledge (traditional knowledge) is an oral tradition. Traditional knowledge has been defined in numerous ways across the literature, but is generally understood as accumulated bodies of knowledge rooted in the spiritual health, culture, and experiences of Indigenous peoples in the occupancy and use of a land base [19–22]. Traditional knowledge represents a cumulative, multigenerational knowledge of local and regional physiography, natural features, climate, wildlife, and an intimate understanding of the relationships between all aspects of the environment, including people [20]. Efforts to map

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traditional knowledge among Indigenous peoples have been widespread since the 1970s in response to concerns about the erosion of traditional culture, the need to improve participatory natural resources management practices, and an interest in asserting legal claims of tenure over traditional lands and natural resources [23–27].

A specific interest in traditional ice use in the circumpolar north emerged in the 2000s, a period during which geospatial technologies experienced radical changes and greatly enabled mapping in the far north [28]. In 2000, the U.S. government began to allow the public to receive a nondegraded GPS signal globally, which facilitated its use in remote regions. The same year, ESRI released Arc IMS 3.0, a web-based Geographical Information Systems (GIS) platform that initiated a wave of innovation in online mapping. Moreover, space agencies and commercial companies began to make increasingly more available high-resolution satellite imagery every year [29].

At the same time, scientists have become interested in using Indigenous traditional knowledge in their research over the past few decades. This is particularly true in the circumpolar north, where the impacts of climate change on the cryosphere have created a sense of urgency to understanding the impacts of global warming to the region. Historical scientific climatological data in the circumpolar north are lacking, except for proxy measures (e.g., sediment cores), but over millennia Indigenous peoples have maintained traditional land-use practices and a detailed knowledge of natural processes. Thus, traditional knowledge can be used to fill key knowledge gaps at local scales [30, 31]. Indeed, many scientists work with traditional knowledge holders due to the paucity of weather- and ice-monitoring data in high-latitude regions of the world, and to increase their understanding of the impacts of climate change in a region. However, traditional knowledge plays a more foundational role than simply patching gaps in data records. It helps scientists to better frame their research in ways that can ultimately produce more usable knowledge to northern communities [32].

Northern Indigenous peoples have also been interested in collaborating with scientists, in the interest of documenting traditional knowledge for cultural preservation and to assert land-use claims over their traditional lands [26, 27, 33], and because rates of environmental change have surpassed anything experienced previously [34]. Indigenous peoples of the north are adaptive by nature [8, 35]; however, climate change has prompted communities to inquire how science and technology can be used alongside traditional knowledge of the land to support their efforts in adapting to climate change.

As a growing body of research has suggested, collaborative research with traditional knowledge holders is successful when it allows the time for a meaningful, co-productive process to develop [36, 37]. The tools and outputs of co-productive geospatial projects may act as boundary objects—collaborative tools or concepts that possess shared meaning within the collaboration—but whose significance differs markedly when collaborating individuals return to their own institutions or community contexts [38, 39]. In other words, traditional knowledge maps and databases can have very different roles in communities than they do in research. Thus, researchers, spatial analysts, and others involved in these collaborations who take the time to consider how the outputs of their research will be used by their collaborators tend to be more effective at creating viable tools that will be used by communities [36, 37].

2. Methodology

This review involved a search of peer-reviewed literature in Google, Scopus, and Web of Science databases in January, 2016. A search string was developed to identify articles that could help identify geospatial tools being used to support adaptations among Indigenous peoples to climate changes in the circumpolar north. Of specific interest were those adaptations pertaining to changes in the cryosphere and to impacts on mobility in the Arctic and sub-Arctic. Our demarcation of the circumpolar north follows that of Ford et al. [7] whose definition of the Arctic includes Alaska, Canada North of 60°N, together with northern Quebec and Labrador, all of Greenland, the Faroe Islands, Iceland, the northernmost regions of Norway, Sweden and Finland, and Russia—including the Murmansk Oblast, the Nenets, Yamalo-Nenets, Taimyr, and Chukotka autonomus okrugs, Vorkuta in the Komi Republic, Norilsk and Igsrka in Krasnoyarsky Kray, and those parts of the Sakha Republic whose boundaries lie closest to the Arctic Circle. However, we also include the Hudson Bay Lowlands (including James Bay) in Canada due to its physical geography and its sub-Arctic climatology. The resulting area has a population of approximately 4 million people, of whom approximately 400,000 and 1.3 million are Indigenous persons [7, 40, 41]. We wanted to know how geospatial technologies are being used in community-based, collaborative research with Indigenous communities. Thus, research that sought to integrate or use as complementary knowledge constructs—traditional knowledge and the natural sciences in geospatial contexts—with a focus on work that prioritizes community-based research and Indigenous ways of characterizing ice systems was the primary object of this literature review. The resultant search queries employed the following terms: "*climate change*," "*adaptation*"; "*Arctic*" or "*sub-arctic*"; "indigenous" or "Aboriginal"; "*GIS*" or "*Geospatial*" or "*remote sensing*" or "*mapping*"; "*ice*" or "*ice monitoring*"; and "community" or "*community-based*."

A limited review of the gray literature was conducted to evaluate and interpret trends in the literature, which included reviews of websites and correspondence with some Arctic scholars. Forward and reverse citations were conducted and produced the included publications on the theme of data management.

We limited our search to publication dates between January 2005 and January 2016 to exclude research using outdated technologies, and to focus on the period during which adaptation research in the circumpolar north has been concentrated (Ford et al. [7]). Excluded were those studies that did not emphasize the use of geospatial technologies, community-based collaboration, and the complementary use of traditional knowledge with the natural sciences, even where such studies may have applications in community-based research. We also excluded studies that focus exclusively on in situ monitoring and make no explicit mention of geospatial tools. We sought publications on sea, lake and river-ice systems, and on ice roads, as these all act as substrates for movement for the Indigenous peoples of the north. However, we expanded our criteria to include a study of icing of pastures, because we felt this work has some bearing on the other studies we looked at. Research that emphasizes bulk transportation through the Arctic was excluded, as were numerous papers in ecology and northern ecosystems. Also excluded were studies of permafrost and glacier systems.

The original search produced 470 peer-previewed articles. These were exported to Endnote for evaluation. Duplicates were removed, and a reading of the abstracts was conducted. After applying the exclusion criteria discussed above, we reviewed 30 articles. Qualitative analysis of the literature involved manual coding of emergent themes rather than coding according to theoretical constructs or previous empirical results [42]. Our reading included some interest in chronology to identify themes relevant to the present research context.

3. Results and discussion

The resulting community-based ice studies in our search are almost entirely centered in coastal Arctic Canada and Alaska, although not exclusively. All but one study focus on sea ice. The three primary themes that emerged were as follows: (1) the documentation of traditional knowledge in community-based research; (2) the complementary uses of traditional knowledge and science to understand local and regional contexts; and (3) the resulting need to manage geographical data appropriately and effectively (see **Table 1**). Here, we discuss these themes and their subthemes that emerged from our examination of the literature. First, we discuss how traditional knowledge documentation produces *living memory maps* that are of considerable value to both researchers and communities, and that act as discursive objects of ongoing research that have implications for how we design geodatabases. These maps are the basis of *ice classification systems*, and some studies further incorporate *remote sensing* with traditional knowledge for local ice monitoring to facilitate safe winter travel. A number of studies use these tools collectively with the aim of developing integrated *early warning systems (EWS).* In this light, the emergence of numerous collaborative geomatics platforms has led to numerous concerns regarding data management in recent years.

3.1. Production of living memory maps

The value of documenting collective memory is discussed throughout the literature as a discursive process. Aporta [5] and Gearheard et al. [43] collaborated with Inuit hunters to map winter trails and document traditional knowledge of wildlife and other features. The resulting maps, developed in consultation with elders and present-day hunters, are described as "living memory maps" [5, 43]. Along with Freeman's work of the 1970s [23–25], these collaborative maps have been among the first documents to show how extensive traditional land use of the circumpolar north is, reflecting a tenure of land that Aporta contrasts with the widely misplaced notion of an unused and largely barren Arctic landscape [5]. Winter trails across the ice, rather, provide important conduits that span the circumpolar north. They are reconstructed each year and are based on knowledge that has been shared orally over many generations. This knowledge includes detailed understandings of ice processes and travel safety, and represents the cumulative knowledge of present-day hunters and of the detailed, intergenerational knowledge held by the elders of a community [5, 44–47]. See **Figure 1** for examples of the kinds of knowledge that are used to create these maps.

Primary research themes	**Geospatial application themes**	**Applications**	**Publication**
Documenting traditional knowledge (TK)	Living memory maps of winter trails and ice use based on participatory TK research	Document of traditional land use and tenure systems	Aporta (2009), Fidel et al. (2014)
		Participatory mapping process enables researchers to actively engage with communities	Aporta (2009), Eisner et al. (2013), Eisner et al. (2009) Gearheard et al. (2010), Herrmann et al. (2012), Laidler et al. (2010)
		Maps of collective memory in a community can be used to facilitate the intergenerational transfer of TK from elders to youth	Isogai et al. (2013), Laidler et al. (2011)
Complementary uses of TK and science to understand local context	Ice classification systems	Classification and mapping of ice types	Druckenmiller et al. (2010), Laidler et al. (2010), Tremblay et al. (2006)
		Used to identify of climate change indicators	Laidler et al. (2010), Tremblay et al. (2006)
	Using TK with remote sensing	Used to identify vulnerabilities and adaptive capacities of communities to climate change	Druckenmiller et al. (2009), Ford et al. (2009), Laidler et al. (2009)
		Using TK validate remote sensing observations	Bell (2012), Gauthier et al. (2010), Kapsh et al. (2010), Laidler et al. (2011)
	Development of geospatially-based early warning systems	Establishment of networks of community-based monitoring teams that integrate TK using geospatial tools	Gauthier et al. (2010), Mahoney et al. (2009), Johnson et al. (2013)
		Integration of community-based ice observation networks, remote sensing tools, seasonal forecasts and decision-making to warn of unsafe conditions for hunting and/or travel	Bell et al. (2014), Druckenmiller et al. (2009) Mahoney et al. (201)
Data management	Development of Geomatics platforms	Designed primarily for engagement with community	Harrmann et al. (2012)

Primary research themes	Geospatial application themes	Applications	Publication
		Intended for ease of uptake and customization	Gardner-Youden (2012), Isogai et al. (2013), McCarthy et al. (2012)
		Employs complex relational databases for integrating multiple data types and sources for enrichment of TK	Eicken et al. (2014), Pulsifer et al. (2011)
		Highly interactive platform to facilitate education and public awareness of community-driven research while protecting intellectual property rights	HBC (2015)
		Large platform designed to enable information sharing and to establish early warning systems	Eicken (2014)
	Respecting indigenous rights	Designing accessible research to enable shared authorship with communities	Johnson et al. (2015), Pulsifer et al. (2015)

Table 1. Themes found in the use of geospatial technologies in community-based research in Arctic and sub-Arctic regions.

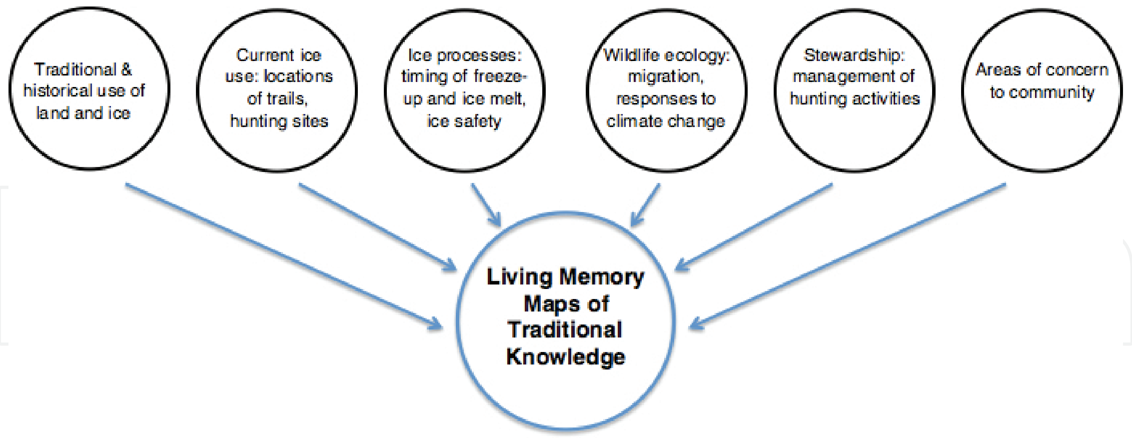

Figure 1. Examples of traditional knowledge used to create living memory maps.

These maps are of significant use to both researchers and community members, but often for different purposes, as illustrated in **Figure 2**. Scientists base much of their work on the details they provide of local ice processes and the potential they offer in helping to build meaningful relationships with communities [44, 45, 48]. On the other hand, communities have been interested in their potential to support local interests in land management, land-use claims,

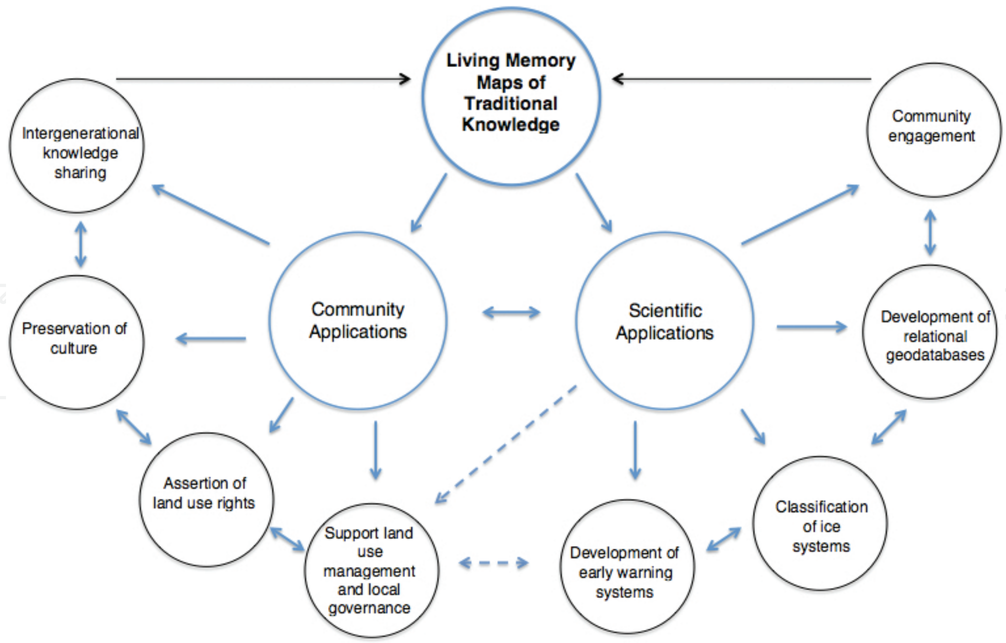

Figure 2. Examples of applications of living memory maps by communities and in research.

cultural preservation, and the sharing of traditional knowledge with younger generations [26, 27, 49]. In some instances, the value of these maps may be the reason why communities collaborate in the first place; so, care in their production and maintenance to reflect this value is important [32]. However, as has been observed elsewhere [50], their value to local governance and natural resources management is not adequately discussed in the literature (expressed by the dashed lines in **Figure 2**). This gap may have implications in terms of how useful the research ultimately is to communities.

In their study of Inuit sea ice use, Laidler et al. [47] use topographic maps in interviews with elder sea ice experts to document and map traditional knowledge of local sea ice. They cite the conversational value of large paper maps to dialog with sea ice experts, employing mylar overlays for documenting spatial information provided by elders, which are later digitized. The ability to converse respectfully and effectively with elders is an important aspect of the mapping process. However, accuracy is lost with digitization at rates inversely proportional to scale. Thus, this approach warrants consideration of the potential benefits of mapping directly into a GIS platform.

This view of traditional knowledge documentation as an ongoing dialog with community participants is a notable theme in community-based traditional knowledge mapping. For instance, there are practical challenges to mapping traditional knowledge due to the fact that traditional knowledge is usually intertwined with stories, place names, euphemisms, and other aspects of a community's culture that can render it incomplete in its documented form [51]. This has underscored the need for relational geodatabases (a topic we will address later in this chapter) to facilitate ongoing inputs of data as they are collected, so that waypoints associated with traditional knowledge documented in interviewed form may be enriched by stories, photography, and other data formats [32, 38]. To this end, one study employs participatory photomapping as a method for documenting, contextualizing, and sharing Indigenous observations of environmental conditions [52].

Methods of traditional knowledge mapping require archival research as a precursor to any new traditional knowledge mapping studies. Of the many traditional knowledge mapping projects that have been already conducted to date, a significant number exist only in paper form, lie on old hard drives, or are essentially lost, having been inappropriately cataloged. Thus, methods for archiving any recovered work from previous traditional knowledge studies are essential [53].

3.2. Ice classification maps

A number of studies have created atlases of ice types based on characteristics drawn from traditional knowledge [6, 48, 54–57]. As Tremblay et al. [48] discuss, this allows a researcher to understand how ice dynamics are perceived from a community perspective, and to conduct ice research using scientific methods based on traditional knowledge of ice and ice safety. Often, based on living memory maps, these studies can include extensive interviews and field surveys with elders and local hunters to photograph and geolocate different kinds of ice, and describe how these ice types are used. Interviews and surveys may document names of ice types in the local language, identify features. and/or processes deemed important to hunters and fishers, and locate important fishing and/or hunting sites where different types of ice may be found. The maps that result establish classification systems of ice as baselines on which the impacts of environmental change and industrial development on ice systems can be evaluated [6, 54–56].

Some studies have identified indicators of environmental change and incorporated them into ice classification systems, either for analysis of potential impacts of climate extremes or climate change on safe travel over ice [48, 57, 58] or to help researchers understand the influences of local geography on ice systems [48]. As **Figure 3** illustrates, the resulting ice classification systems demonstrate how traditional knowledge, science, and geospatial tools can be used together to synthesize valuable tools for managing ice safety.

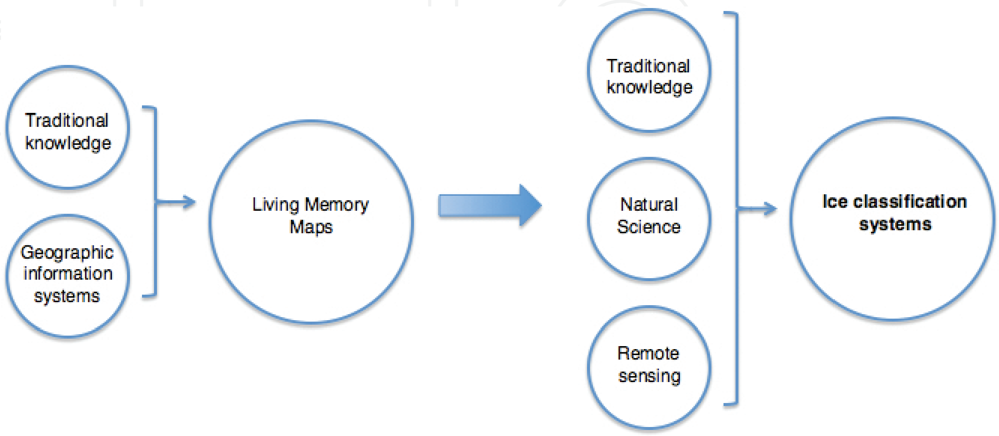

Figure 3. Ice classification systems are based on the complementary use of traditional knowledge, science, and geospatial technologies.

3.3. Synthetic aperture radar (SAR) imagery in ice monitoring for safe winter travel

A number of studies have explored the use of SAR imagery in ice safety monitoring. SAR uses an active microwave sensor that provides imagery, regardless of cloud cover or time of day (unlike optical imagery), and employs radar to interpret and map surface and near-surface characteristics of ice [59]. Its resolution is generally more appropriate for use at scales that are used by hunters [60]. Passive microwave imagery, which has a coarser resolution than SAR but broader spatial coverage, was used in one study of walrus hunting in Alaska to evaluate regional anomalies in sea ice concentrations, but the resultant anomalies were unable to be resolved with local sea ice use due to problems with scale and the resolution of the imagery [61].

Ice monitoring studies aim to provide communities with tailored remote sensing [54, 62] or map products [6, 55, 56] to help individuals in communities plan their travel across ice. Laidler et al. [62] evaluate an Inuit community's interests in tailored SAR products, and results indicate that Inuit hunters are interested in using satellite imagery (and were using it previous to the study), but would prefer to have the following: higher resolution and higher frequency SAR images; time series of images as well as supplemental optical imagery to help better elucidate details themselves from the images; image interpretation training; and opportunities for collaborations directly with the agency processing the SAR imagery, so that traditional knowledge could inform and improve on how images are interpreted on an ongoing basis.

Some studies have explored how traditional knowledge can do just that—that is, meaningfully inform the validation and processing of remote sensing imagery—for community use [6, 54]. For example, a study in Nunatsiavut (Labrador, Canada) aimed to develop a processing and validation methodology to incorporate sea ice thickness data and satellite imagery into a knowledge database of both Inuit- and WMO-based ice catalogs. Their goal is to streamline the generation of products that they process in accordance with user needs, and based on extensive community consultation.

In another study of river ice in Nunavik (Quebec), SAR imagery and the FRAZIL GIS-based hydrological modeling tool are used to create ice maps for safe winter travel planning [6]. This study is significant in that it demonstrates how advances in the RADARSAT-2 satellite technology (multipolarization, polarimetry, and higher spatial resolutions) have the ability to discriminate between freshwater types, and how improved image delivery times have enabled near real-time use of the technology [6]. However, the authors also indicate that validation of satellite imagery in their study was complicated by the difficulty in accessing key sites on the rugged, remote landscape of the study site. They opted to use ground-based cameras and aerial photogrammetry with limited success, and improvements to their radar mapping process were deemed necessary. Today, this could be made possible with unmanned aerial vehicle (UAV)-enabled photogrammetric validation, which has recently been studied for its potential in gaining access to remote Arctic and sub-Arctic sites as a remote sensing tool [63]. Other options for validation include the potential of community-based volunteer monitoring programs to work closely in collecting data, for which there is extensive guidance from previous research [64, 65].

As exemplified by Ford et al. [58], when climate indicators are obtained, sea ice observation data and classification systems can be used with sea ice charts (these are SAR-based maps of ice concentrations provided in Arctic coastal areas by the Canadian Ice Service) to better understand community vulnerabilities to climate change. Where SAR is available, sea ice concentrations can be studied directly as has been done in studies of walrus hunting in the Bering Strait of Russia and Alaska [66].

3.4. Use of other remote sensing imagery

While the majority of adaptation and ice monitoring research with Indigenous peoples has emerged out of North America [7, 37], in Eurasia the Sami reindeer-led initiative, the EALÁT Project, has used remote sensing and participatory Geographical Information Systems (GIS), with the end goal being the establishment of an early warning system with respect to seasonal climate impacts on herding grounds [67]. Remote sensing has been used in a collaborative classification system to identify where the seasonal icing of pastures occurs. Icing effectively "locks out" reindeer from their food source (lichen) and force nomadic herders out of traditional herding routes. EALÁT has developed vegetation indices collaboratively with herders using MODIS, SAR, and Lidar, and notably has developed an integrated approach that includes the seasonal forecasting of icing events to facilitate on-the-ground land-use decision-making during "lockout" seasons. This kind of early warning system, which brings traditional knowledge and seasonal forecasting together through extensive collaboration and knowledge coproduction, can allow for the early detection of unsafe conditions. This is what others have called for in other regions of the circumpolar north in the face of climate change [32].

3.5. Collaborative geospatial platforms and data management

With the growth of traditional knowledge mapping, rights to intellectual property and free and informed prior consent have featured prominently in the design of geospatial systems for research with Indigenous communities [33]. However, the numerous legal and ethics-based protocols that exist can be unclear for both the community and the researcher in terms of who has the authority to use or share data through community-based research [37]. Many technical solutions do exist—such as systems with multiple access roles, data encryption, and protection of sensitive sites—but these require highly technical skills that may be out of reach of some communities or research projects.

A number of geospatial platforms have emerged to provide geospatial services in traditional knowledge mapping, to work respectfully with communities, and to establish appropriate protocols for mapping and managing traditional knowledge data. These include the Exchange for Local Observations and Knowledge of the Arctic (ELOKA) program (National Snow and Ice Data Center), the Geomatics and Cartographic Research Centre's Inuit *SIKU* Sea Ice Atlas (Carleton University), the Interactive Knowledge Mapping Platform for Community-Driven Research (Arctic Eider Society), and an emerging collaborative geomatics tool being developed for use in sub-Arctic Canada (the Centre for Community Mapping and the Computer Systems Group, University of Waterloo). Each of these tools is rooted in research networks particular to given regions, and brings together numerous local and regional projects into one platform [38, 68].

Some scientists have called for greater data sharing and partnerships to reduce ice-related hazards [56]. In light of this, data management has emerged as a prominent issue, particularly in the high Arctic, where most of the community-based traditional knowledge research on ice has occurred [37, 38, 69, 70]. Principles of "Indigenist data management" have been called for and are rooted in the context-specific nature of traditional knowledge, and the need for relationship-building and a respect for Indigenous values, culture, and language in research [38]. Enabling communities to share their own data at their own discretion at conferences or with other communities or researchers should be a priority for the design of geospatial platforms. Yet, this is complicated by the fact that data generated during research can be in diverse formats, such as recorded narratives, qualitative observations, transcripts, various types of multimedia, and geodatabases. Providing meaningful accessibility to archives of these assemblages of data remains a challenge [37, 70]. Additionally, a lack of access to technology and slow Internet speeds persist in the north, and must be reflected in the development of plans to store and share data [37].

3.6. Gaps in the literature

Studies involving sea ice are well characterized in the literature. However, comparable studies of ice use in brackish and inland freshwater systems were found to be notably underrepresented in community-based geospatial research. Neither lake-based nor ice road studies are represented at all, and only one community-based river ice study was found. This may be due to fewer remote sensing tools available in inland contexts; there are no ice charts, for example. Algorithms have yet to be developed with which to characterize river ice effectively in the processing of SAR imagery; however, anticipated enhancements to the RADARSAT constellation planned for 2018 may benefit freshwater research [59]. Additionally, in situ monitoring can be used effectively on freshwater lakes to validate imagery [10].

There was a concentration of research among communities that participated in the International Polar Year (IPY)-affiliated projects, which were centered in the high Arctic. This signifies both that the funding provided by the initiative was instrumental in advancing community-based geospatial research on ice systems, and that a lack of other sources of funding has hindered research where IPY research sites and priorities did not occur. Virtually, all of the work was in coastal communities, primarily in Canada, and to a lesser degree, Alaska. IPY Canada decidedly prioritized research that was community-based [69], indicating that the field of community-based research on ice has been advanced by the IPY initiative. By contrast, a paucity of community-based studies outside of Arctic North America was noted, and this was also seen with respect to the sub-Arctic regions of the world, including Canada. Studies conducted in freshwater regions and on ice roads have also been relatively rare, which is particularly noteworthy given their role in supporting northern livelihoods.

Finally, we agree that the potential for an early warning system approach to ice research should receive greater emphasis, as continued warming and amplification of polar temperatures in the polar regions will negatively impact ice-based travel in the Arctic and sub-Arctic regions of the world. Such early warning systems may focus on establishing how geospatial technologies can be used to detect dangerous ice conditions earlier or in real time, and help communications within community and between communities located in high-latitude regions, increasing the adaptive capacity of these communities.

4. Conclusion

Geospatial technologies have helped scientists work with Indigenous peoples to document and map traditional knowledge, and develop tools for cataloging ice systems. This documentation process, more of a dialog than a series of data-collection procedures, has produced geodatabases and maps that are valuable to both researchers and communities for different reasons. Tools, both old and new, are used to create living memory maps and ice classification systems, which can be used to inform scientific inquiry on climate change, impacts to local ice systems, and ways of using the ice.

Remote sensing has been an important part of this process, and the current movement toward tailoring image products in collaboration with communities is exciting. However, the ultimate goal of creating community-based tools to improve ice safety requires expanding the scope of research to outside North America, to be inclusive of sub-Arctic regions of the world, as well as inland freshwater systems, since communities located in these regions and systems also are similarly impacted by climate change and resultant safe winter-travel concerns. Finally, the end goal of setting up an integrated early warning system will require greater partnership building between research teams and community members, and the establishment of meaningful data management systems that facilitate knowledge sharing while addressing community interests and concerns.

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