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Contributions and perspectives of Indigenous Peoples to the study of mercury in the Arctic

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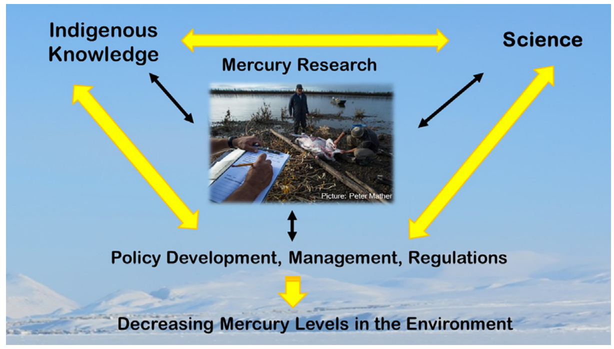
HIGHLIGHTS

- Indigenous Peoples greatly contribute to Arctic Hg research and monitoring
- Insights into key involvement of Indigenous Peoples in Hg study are provided
- Over 40 examples of Hg research conducted with/by Indigenous Peoples are presented
- Indigenous Knowledge in research and decision-making is being increasingly recognized
- Co-production approaches of scientists and Indigenous Peoples in research are key

GRAPHICAL ABSTRACT



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ABSTRACT

Arctic Indigenous Peoples are among the most exposed humans when it comes to foodborne mercury (Hg). In response, Hg monitoring and research have been on-going in the circumpolar Arctic since about 1991; this work has been mainly possible through the involvement of Arctic Indigenous Peoples. The present overview was initially conducted in the context of a broader assessment of Hg research organized by the Arctic Monitoring and Assessment Programme. This article provides examples of Indigenous Peoples' contributions to Hg monitoring and research in the Arctic, and discusses approaches that could be used, and improved upon, when carrying out future activities. Over 40 mercury projects conducted with/by Indigenous Peoples are identified for different circumpolar regions including the U.S., Canada, Greenland, Sweden, Finland, and Russia as well as instances where Indigenous Knowledge contributed to the understanding of Hg contamination in the Arctic. Perspectives and visions of future Hg research as well as recommendations are presented. The establishment of collaborative processes and partnership/co-production approaches with scientists and Indigenous Peoples, using good communication practices and transparency in research activities, are key to the success of research and monitoring activities in the Arctic. Sustainable funding for community-driven monitoring and research programs in Arctic countries would be beneficial and assist in developing more research/monitoring capacity and would promote a more holistic approach to understanding Hg in the Arctic. These activities should be well connected to circumpolar/international initiatives to ensure broader availability of the information and uptake in policy development.

1. Introduction

Arctic Indigenous Peoples are among the most exposed humans when it comes to foodborne Hg contamination (Basu et al., 2022). Mercury research in general investigates issues that are prerequisites of food security for Indigenous Peoples: the levels of Hg in the Arctic have ramifications for the safety of the traditional diet, which is part of the foundation of the life, health and culture of Arctic Indigenous Peoples (ICC-Alaska, 2020). In order to address these issues, the monitoring and research of contaminants has been on-going in the circumpolar Arctic for decades. This work has been mainly possible because of the involvement of Arctic Indigenous Peoples.

Historically, Arctic Indigenous Peoples have for a long time been considered as research 'subjects', or bystanders, in a research approach associated with colonialism and closely tied to exploitation and racism (Wiseman, 2015; ITK, 2018; Moon-Riley et al., 2019). Relationships between Indigenous Peoples and researchers are gradually improving and, in recent years, some of these relationships have developed into mutually beneficial partnerships, but this practice is still not the norm (ITK, 2018). To date, Indigenous involvement in environmental research and monitoring has ranged from limited participation (e.g., performing sample collection) to full partnership in a co-production approach (David-Chavez and Gavin, 2018; Thompson et al., 2020). A multi-decadal analysis of participatory inclusion of Indigenous Peoples in northern research revealed only a slight increase in their involvement during the period from 1965 to 2010 (Brunet et al., 2016). Nevertheless, Indigenous organizations and regional governments are increasingly spearheading their own research efforts, thereby fulfilling their need of Indigenous self-determination in research (Brunet et al., 2016; ITK, 2018; Schott et al., 2020). Researchers have to acknowledge and respect the fact that Indigenous Knowledge (IK) can help, among other things, to direct research priorities and processes, and can be used to determine what research is done and how. Indigenous Knowledge should also be considered as its own distinct body of knowledge owned by the knowledge holders (FNIGC, 2007; ITK, 2018). Indigenous Knowledge is acquired through year-around observations over millennia and includes a holistic and wide range of continuously evolving perspectives (Johnson et al., 2015; Lennert, 2016; Mantyka-Pringle et al., 2017). It should be noted that while many published articles refer to IK and Traditional Knowledge interchangeably in an Arctic context, the term Traditional Knowledge is not limited to Indigenous Peoples and can be used for any groups with distinct cultures (Dahl and Tejsner, 2020). For this reason, and because Traditional Knowledge is often (mis)understood to only refer to the past, many Indigenous Peoples prefer the term "Indigenous Knowledge" which is inclusive of its ever-evolving dimension. The term "Indigenous Knowledge" is also preferred by five of the six Permanent Participants organizations of the Arctic Council (https://arctic-council.org/about/permanent-participants/). Arctic Indigenous Peoples are represented in the Arctic Council by the Permanent Participants, and six Indigenous Peoples' organizations have been granted Permanent Participants status in the Arctic Council (Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Inuit Circumpolar Council, Russian Association of Indigenous Peoples of the North, and Saami Council). However, different regions and peoples have various preferences and practices when referring to their knowledge (see Table S1 of Supplementary Material; SM).

In this article, we offer an overview of the contributions of Indigenous Peoples to Hg monitoring in the Arctic, and discuss approaches that could be used, and improved upon, when carrying out these activities. This multidisciplinary work was initially conducted in the context of a broader assessment of Hg research under the Arctic Monitoring and Assessment Programme (AMAP) (AMAP, 2021a). It highlights methodology and connections at the interface between humans and their environment in the Arctic, which has led to the critical development of information on Hg contamination. This article is not a systematic review of the literature nor a scientific and/or historic analysis of Indigenous involvement in contaminant research but rather provides a general overview of Indigenous involvement in Hg studies across the circumpolar Arctic.

The information presented herein was collected by the two first primary authors who initially contacted Indigenous Peoples, groups, organizations, communities, and partnering researchers within their professional networks. People contacted were invited to identify the leaders of relevant projects, as well as to name others within their networks who may be engaged in and/or aware of Hg projects led or co-led by Indigenous Peoples (snowball sampling method; Denzin and Lincoln, 2018). Projects were also considered where Hg was not the central focus of the research but was one feature. We purposefully relied on searches through professional networks for identifying relevant projects rather than conducting a literature review. The latter would have biased project selection towards projects that are represented in the peer-reviewed academic literature, which may not always be applicable to Indigenous-led initiatives and projects involving IK (see Alexander et al., 2021 for a more in-depth discussion).

The development of this work therefore is based exclusively on contributions and comments from Indigenous representatives, community-based project leaders and collaborating scientists. Information pertaining to the specific examples described below were provided by the principal investigators of projects; only projects where leaders provided a response and were willing to contribute content were included and all are listed as contributing authors. Projects outlined in this paper included an Indigenous Knowledge component that ultimately contributed to a greater understanding of Hg contamination and effects in the Arctic, and also reflected availability/capacity of research teams to contribute to the paper.

2. Background of Indigenous Peoples' contributions to mercury environmental monitoring and research in the Arctic

Monitoring of the Arctic did not begin with the introduction of formal scientific environmental monitoring (Pfeifer, 2018). Arctic Indigenous Peoples have relied on their knowledge, which is passed down from one generation to the next to observe and understand the environment they live in and are a part of (ICC-Alaska, 2015; Johnson et al., 2015). This knowledge on environmental conditions, wildlife and vegetation has been the basis for their survival, culture, and sense of locality (Lennert, 2016). It represents a place-specific and long-term understanding, which in symbiosis with scientific research can lead to a better understanding of the changing environment and the interactions between components of the Arctic environment. The value of IK to general understanding, including research and policy development, has been increasingly recognized by scientists and governments in the Arctic and beyond (Danielsen et al., 2014; Mantyka-Pringle et al., 2017; Arctic Council, 2018; Ban et al., 2018; Government of Canada, 2019a, 2019b), and the inclusion of IK and the involvement of Indigenous communities in decision-making processes has been found to result in more efficient and adaptive management (Danielsen et al., 2010). There are many examples of environmental monitoring activities involving and/or being led by Indigenous communities or regions across the Arctic (Johnson et al., 2015; Johnson et al., 2016). An exhaustive list outlining and describing all these activities in detail is beyond the scope of this article. We will present here examples of circumpolar Arctic initiatives that involve Indigenous Peoples and mobilize IK in relation to the study of Hg monitoring and research.

2.1. Government and policy context

Many regional and local governments in the circumpolar Arctic conduct environmental monitoring and/or research activities to support local food security and general policy as well as decision-making processes; IK plays an important role in these activities. In Canada, various agreements and programs have helped to recognize the effective role of Inuit, First Nations and Métis in wildlife and resource management, as well as in policy and program development. In Nunavik (Québec, Canada), the Nunavik Research Centre (NRC) was established in 1978 to monitor and collect land use and ecological data in the region (Makivik Corp., https://www.makivik.org/nunavik-research-centre/). The NRC operates a number of ongoing wildlife monitoring programs, often working with external scientists, but under the mandate that their research responds to the needs, questions, objectives and concerns of Nunavimmiut (residents of Nunavik) and respects and utilizes Inuit values and knowledge in the process. In the Inuvialuit Settlement Region (ISR, Canada), bodies such as the Fisheries Joint Management Committee (FJMC) were created as part of the Inuvialuit Final Agreement (IFA, 2005). It provides advice to the Minister of Fisheries and Oceans (DFO) on all matters affecting fisheries and the management of fish and marine mammals found in ISR. The FJMC also works closely with government agencies, renewable resource user groups in the Inuvialuit communities and other renewable resource boards in Canada and Alaska that oversee common migratory stocks. Alongside the Gwich'in, the Inuvialuit have also been integral in the Arctic Borderlands Ecological Knowledge Society (ABEKS)'s environmental monitoring program that documents and contributes local knowledge to co-management in the range of the Porcupine caribou herd (*Rangifer tarandus granti*). First Nations in Northwest Canada have increasingly been stewarding their traditional territories by launching Guardian Programs that vary greatly in their scope but often engage in ecological and climate monitoring. Since 2004, the Aboriginal Aquatic Resource and Oceans Management (AAROM program) has also been supporting Indigenous groups, particularly First Nations and Métis, to manage aquatic and ocean resources as well as to participate in related advisory, co-management and decision-making processes.

In jurisdictions of other countries, Indigenous Peoples and their knowledge are not considered to be distinct entities. For example, Greenland is a self-governing territory where most of the population consists of Inuit, but no specific structure for IK inclusion within the political decision-making system has been established. Through the Act on Greenland Self-Government from 2009, which constitutes an extension of powers from the Home Rule Act of 1979, the people of Greenland are a people pursuant to international law with the right to self-determination (Act on Greenland Self-Government, 2009). While the Self-Government Act does not mention Indigenous Peoples as such, the Act also established the Greenlandic Inuit language as official language. Furthermore, in the sustainable management of natural resources, including through monitoring, a strong emphasis is put on the knowledge of hunters, fishers and the local communities, but there is no differentiation between IK and local knowledge. The Government of Greenland is obliged through the Parliament Act on Hunting to consult with biologists and the Fisheries Council and Hunting Council on all general management issues. Hunters and fishermen organizations are standing members of the councils. Furthermore, the Government has an obligation to receive input from the hunters and users of marine mammals in the decision-making processes. Additionally, the Greenland Institute of Natural Resources, whose mandate is to provide the scientific basis and advice to the Greenland Government on the sustainable utilization of living resources (such as fisheries and hunting quotas), includes local knowledge in its scientific work.

2.2. Defining community-based monitoring and research

In addition to more formalized regional research and environmental monitoring activities, many Indigenous communities have established their own projects and have been, or are currently, involved in studies and/or ongoing monitoring activities led or co-led by academic, government, non-governmental organizations, and/or consultant scientists. In the literature, these activities are often referred to as “community-based” research (CBR) or monitoring (CBM), terms that are predominantly used in North America. It should be noted that in some regions, the terms "community-led" or "community-driven" monitoring are preferred, and sometimes used in this paper, to reflect Indigenous leadership in monitoring initiatives. Some monitoring projects carried out in partnership with Indigenous Peoples and/or Indigenous organizations may also involve a "co-production of knowledge approach" which brings together different knowledge systems (IK and science) while building collaborative and equitable partnerships (ICC, 2016; Yua et al., 2022).

Formal monitoring initiatives that describe themselves as "community-based" can use different approaches to community engagement. One approach is for government or academic researchers to recruit community members to collect data or samples for studies driven by the information needs of institutions located outside the community. But from an Indigenous perspective, CBM or CBR ideally means that a community determines the reason for the research or monitoring project, which addresses a concern or issue as identified by the community based on their needs, priorities and interests (Johnson et al., 2015). Therefore, another approach is for the community to be involved in all stages of the project (and to lead or co-lead it): from planning to implementation and data collection, interpretation and analysis, dissemination, communication and sharing of data, to the application of data for decision-making. This Indigenous definition of community-based research falls more in line with the qualitative research definition of "Community-Based Participatory Research" which is often defined by equal partnerships and equal decision-making powers (Minkler et al., 2012). In an Indigenous community, CBM/R done in full meaningful partnership with IK holders is more likely to utilize IK as deemed appropriate by the Indigenous partners.

To gain a better understanding of the current state of community-based monitoring in the Arctic, a multi-year initiative was launched in 2012 by the Sustaining Arctic Observing Networks (SAON), which yielded an in-depth report of 81 programs across the circumpolar Arctic (Johnson et al., 2016), as well as the development of a searchable online atlas, the Atlas of Community-based Monitoring and IK in a Changing Arctic (SAON, 2021). While the CBM atlas does not focus on contaminants, several projects listed in the atlas also include work on contaminants, and some of the projects included herein are featured in the CBM atlas.

3. Examples of mercury monitoring and research done with/by Indigenous Peoples

A wide variety of monitoring and research programs, particularly those investigating contaminant levels in wildlife and fish, benefit from understanding the environmental and ecological contexts in which the research is being done, which IK is uniquely positioned to offer. Ongoing observations by Indigenous Peoples on sea-ice coverage and climate conditions, animal distribution, behavior, diet and body condition, the characteristics of prepared foods and so on can substantially enhance the interpretation of results related to contaminants levels, which is particularly visible in CBM/R studies.

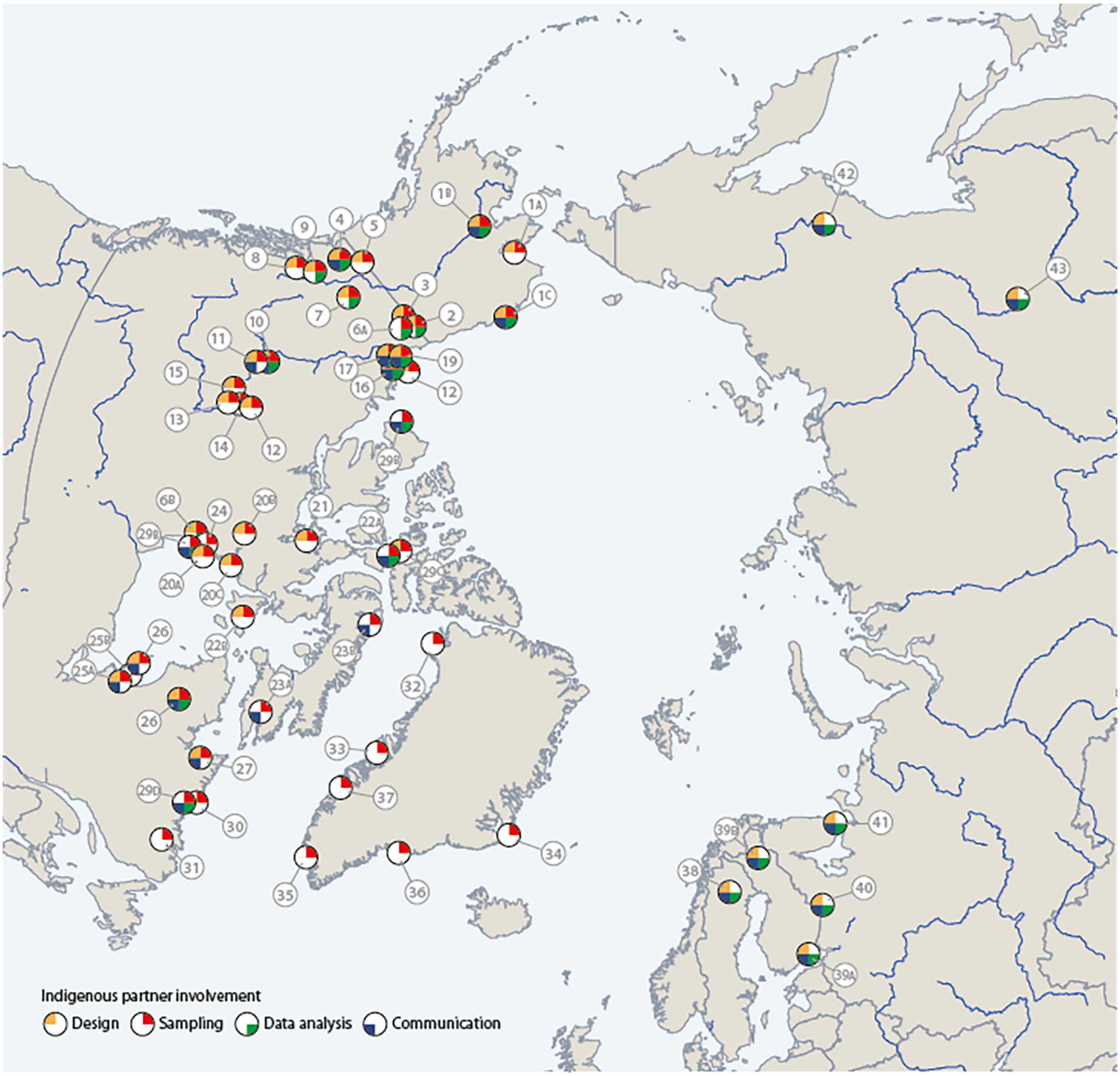
Indigenous Peoples from several regions of the Arctic have been involved to varying degrees in Hg environmental monitoring and research (see Fig. 1). With respect to Greenland, at least five large towns and villages have consistently participated in such work, including Qaanaaq, Qeqertarsuaq, Nuuk, Tasiilaq/Kulusuk and Ittoqqortoormiit (Glahder, 1995; Dietz et al., 2001; Sandell et al., 2001; Born et al., 2011). Community partnerships and Inuit knowledge and local knowledge are essential in East Greenland due to their input on sampling and interpretation of information from biological markers in wildlife exposed to contaminants and diseases. In Canada, numerous communities in Nunatsiavut (Labrador), Nunavik (Québec), Nunavut, the Inuvialuit Settlement Region (ISR), the Northwest Territories, and Yukon have led or participated in wildlife and human contaminants biomonitoring and related research projects. Many of these studies have been supported for more than 30 years by the Northern Contaminants Program (NCP; Crown-Indigenous Relations and Northern Affairs Canada, CIRNAC), as well as by local, provincial/territorial and national organizations. The consistent source of funding and the requirement of collaboration between Indigenous communities/organizations and scientists is a unique aspect to the NCP, which explains the high number of Canadian examples found in this paper. In other Arctic countries, community-based research and monitoring efforts that focus on Hg are mainly localized efforts undertaken by communities in partnership with academic researchers and/or independent organizations, making them harder to capture.

Multiple projects are described in more detail in the following section. Additionally, it needs to be recognized that Indigenous Peoples have a holistic understanding of their environment, and while some of the CBM projects may not have a focus on Hg it may be recognized to play a role in environmental and human health and be investigated as one factor among others. Therefore, projects involving Hg research were also included in the present article even where Hg was not the central focus. Finally, several of the described projects provided Hg data that are included in articles from this Special Issue (Morris et al., 2022a; Chételat et al., 2022; McKinney et al., 2022). The map in Fig. 1 and following descriptions are just an indication of the breadth of existing Hg contaminant projects by region and not a complete list of CBM initiatives investigating Hg in the Arctic. More details for each project can be found in the AMAP Hg assessment (AMAP, 2021a); see also SM Table S2 for information.

3.1. United States of America — Alaska

In Alaska, the Native Village of Kotzebue (Tribal Government) has been investigating Hg in subsistence species in Kotzebue Sound and surrounding areas using community-based and holistic perspectives (Fig. 1, project #1A). Earlier research in the mid-1990s directly addressed community concerns about the potential role of contaminants (e.g., radioisotopes and heavy metals) in response to a caribou mortality event. Since 2004, collaborative studies were developed between researchers and the Environmental Program at the Native Village of Kotzebue, as they work together on the Hg assessment of mostly marine biota in Northwestern Alaska. The partnership between professional researchers (primarily in academia) and the local tribal community began with outreach by the Tribe to local academic scientists to begin a formal relationship to identify mutual research priorities that continues today. Areas of interest and research questions were cooperatively developed between the Tribe, their IK holders (harvesters of fish and wildlife) and the researchers. The studies often involve graduate students and are published in peer-reviewed publications. The cooperative and strategic sharing of resources and the technical skills of researchers and tribal citizens were integrated into formal and informal discussions and research products. Short-term studies were then carried out in an effort to develop an understanding of baseline information and drivers of Hg concentrations (including nutrients and other elements) in subsistence species, primarily fish and ice seals (Moses et al., 2009; Cyr et al., 2019). Indigenous Knowledge has been the motivating and organizing force behind the Kotzebue collaborative studies and was used to elucidate the context for the local ecology (i.e., local species and their trophic level relationships) and to identify the species most of interest to local consumers. Indigenous hunting and fishing expertise and knowledge have been critical for the donation of samples with local members of the teams playing key roles within practical and logistic aspects of the partnerships. Finally, local members have guided the development of responsible and effective ways to return information to community members; information is reported back to the community in a multimedia fashion and in detail (i.e., on specific tissues and preparation methods along with cost/benefit information related to nutrition, contaminants risk and cultural factors) such that consumers can safely and confidently make choices about their subsistence foods. These efforts were integrated with the State of Alaska Fish Biomonitoring Program to assure reliable and consistent advice to the community.

A further example of effective collaboration between IK holders and scientific researchers is the Indigenous Observation Network (ION), a community-based water quality and active layer/permafrost program, established in 2006 by Yukon River Inter-Tribal Watershed Council (YRITWC) and the U.S. Government (Fig. 1, #1B). The program has been developed to assess climate change impacts to surface water in the Yukon River basin but expanded its focus to support the White River First Nation



ID	Species/ matrices studied
1A	Seals, fish, caribou
1B	Water, sediment, permafrost
1C	Bowhead whale, seals, walrus, polar bear, beluga
2	Muskrats
3	Fish
4	Fish
5	Fish
6	Caribou (Qamanirjuaq and Porcupine herds)
7	Moose, fish
8	Moose, fish
9	Fish
10	Humans (hair, blood, urine)
11	Water, sediment, zooplankton, benthic invertebrates, fish
12	Invertebrates, fish
13	Fish, water, sediments
14	Fish
15	Fish

ID	Species/ matrices studied
16	Fur bearers
17	Burbot
18	Beluga whales
19	
20	Lichens, mushrooms, seaweed
21	Fish
22	Seabirds (eggs, tissues)
23	Ringed seals
24	Polar bears
25	Blue mussels, sea urchins, plankton, marine fish, common eiders, ringed seals
26	Marine, freshwater, terrestrial assessments
27	Water, sediment, lichen, fish, birds, seals
28	Humans (blood, urine, hair, blood) and country foods
29	Ringed seals
30	Ringed seals and preys
31	Water, invertebrates, fish, ringed seals

ID	Species/ matrices studied
32	Polar bears, ringed seals, black guillemots, sculpins
33	Ringed seals, black guillemots, sculpins
34	Polar bears, ringed seals, black guillemots, sculpin
35	Caribou, Arctic char
36	White-sided dolphins, pilot whales, killer whales
37	Harbor porpoises
38	Freshwater, northern pike, reindeers
39	Northern pike, burbot, reservoir accumulation, sea eagles and other apex predators
40	Northern pike, perch, burbot, reservoir accumulation, human health, other apex predators
41	Soviet-era chemicals, Ponoi river
42	Kolyma fish, reservoirs
43	Water quality, fish, human health

Fig. 1. Examples of community-based/led Hg monitoring and research activities involving Arctic Indigenous communities and regions described in this article; numbers identify projects in the figure and text. Project leads have contributed this information. For further details on the projects consult the SM Tables S2.

and Carcross/Tagish First Nation water governance efforts and to address Alaska Native Tribes' subsistence resources concerns with water sampling for Hg around landfills over the years (Community reports available at https://www.yritwc.org/science and https://www.yritwc.org/library). Local community concerns have been also addressed by conducting water and sediment sampling at historical and present mining sites around

Birch Creek, Tanana, Hughes and the Ruby region for Hg analysis. All data generated by these projects, including IK, are owned by the Alaska Native Tribes and First Nations. The scientific directives for projects are based on the resolutions adopted by the Alaska Native Tribes and First Nations signatories every two years at a summit hosted by the YRITWC. These resolutions can be related to specific regional/local or watershed wide concerns for water resources. The science team identifies funding opportunities and partners, implements projects and disseminates the results/outcomes via community reports, as well as presenting directly project results and updates to the signatories Tribal and First Nation governments. The program relies on communities' input for sampling strategy development, which is based on their knowledge of the area, temporal information about any environmental changes and relies on their logistical support. The ION is also a partner on the ongoing Arctic Great Rivers Observatory (ArcticGRO) project which investigates the Hg export from major Arctic rivers (e.g., Zolkos et al., 2020).

Since the early 1980s, food safety concerns over adverse health effects of contaminants in whales and subsistence consumers on the North Slope (Alaska) led to the monitoring of contaminants, including heavy metals, in foods with a focus on the bowhead whale (*Balaena mysticetus*) (Fig. 1, #1C). This collaboration has been led by the North Slope Borough Department of Wildlife Management, the Alaska Eskimo Whaling Commission and the captains association of the 11 whaling communities (Braund et al., 2018). The bowhead whale monitoring program has resulted in one of the longest time series of contaminant information on an essential Arctic subsistence species (Bolton et al., 2020; Schultz et al., 2020). This co-production of science and the IK-based interpretation of ecological, physiological, behavioral and pathological phenomena has been expanded to include other important marine mammal subsistence resources such as ice seals, walrus (*Odobenus rosmarus*), polar bears (*Ursus maritimus*) and belugas (*Delphinapterus leucas*). The collaboration with hunters and community members is essential for this ongoing monitoring. This joint work depends greatly on IK and on the sharing of knowledge which are done through organized meetings or time spent on the ground or on the water with community members. Hunters and communities provide rich and meaningful spatial-temporal scale wildlife information such as diet, migration patterns, or unusual behavior of animals as well as data on traditional subsistence resources (e.g. the quality or condition of food products) and the environment.

3.2. Canada

3.2.1. British Columbia, Yukon and Northwest Territories

The vast Arctic territories of Canada are inhabited by numerous Indigenous communities including those of Inuit, First Nations, and Métis populations. Many Hg-related initiatives have been developed by Indigenous groups in collaboration with scientists in Canada. Studies across the country generally aim at understanding the presence and accumulation of Hg in fish, wildlife and the environment. This information assists Indigenous Peoples in informed decision making with regards to their diet. Most of these projects have been initiated following concerns of the communities. More details on Canadian projects can be found in SM Table S2 as well as in Chapter 9 of the AMAP Assessment 2021: Mercury in the Arctic (AMAP, 2021a).

In the Yukon, several Hg projects in fish and wildlife have been initiated, developed and carried out by First Nations. In 2007, a project on environmental change and traditional use of the Old Crow Flats, Yukon (Yeendoo Nanh Nakhweenjit K'atr'ahanahtyaa) was established (Wolfe et al., 2011) (Fig. 1, #2). This project, a collaboration between the Vuntut Gwitchin First Nation, the Government of Canada, Department of Environment (Government of Yukon), and university researchers, included the measurement of Hg concentrations in muskrat (*Ondatra zibethicus*) tissues to verify that this traditional food source remained safe. In 2014, in the same region of Old Crow, Hg was investigated in seven species of fish collected by the community to assess healthy food choices for northerners, which assisted in sample preparation for Hg analysis (Fig. 1, #3). It was found that species, age, and fish length were related to Hg concentrations (NCP, 2017). In 2015, Kluane First Nation, based in southwest Yukon, initiated a study on Hg in lake trout (*Salvelinus namayush*) and lake whitefish (*Coregonus clupeaformis*) in Kluane Lake that complemented an existing food security initiative (Fig. 1, #4). University researchers worked in support of the First Nation; Indigenous harvesters and youth collected and processed fish, and the local council supported a youth exchange to the involved universities, where they learned how to analyze fish for Hg and age. Youth also communicated results back to the community at the First Nation annual general assembly and through radio interviews. The youth exchange was meant not only to build capacity but also to empower youth in undertaking cross-cultural stewardship initiatives, to expose them to the post-secondary environment, and to generate a positive experience in applying and working with science, technology, engineering and math (STEM) skills. The process and results were featured in an Indigenous-led film called “Remembering Our Past, Nourishing our Future” (Kluane First Nation, 2016). In Yukon, fish are also currently being collected for Hg measurement by the White River First Nation in Beaver Creek (Fig. 1, project 5). This project was initiated, designed and carried out by the White River First Nation with some assistance by scientists.

The First Nation in Old Crow is involved in the annual Hg assessment of the Porcupine caribou herd (Fig. 1, #6) (see Morris et al., 2022a). Ongoing discussions between the Vuntut Gwitchin Government and the Porcupine Caribou Management Board continue to refine the project in terms of additional questions to ask and variables to consider (e.g. how climate change is affecting migration patterns) when analyzing and interpreting Hg concentrations in caribou. Mercury is also currently being measured in moose (*Alces alces*) and fish collected by the First Nation of Na-Cho Nyak Dun in Mayo, which have been responsible for the project from the conceptualization to the execution with some assistance from a scientist (Fig. 1, #7). Similar projects in moose and fish were initiated in Atlin (Northern BC) and Carcross (Yukon) by the Taku River Tlingit First Nation and the Carcross/Tagish First Nation, respectively (Fig. 1, #8). All three projects were initiated by the individual First Nations to determine contaminant levels in their traditional foods and whether those foods remain healthy choices. In some cases, there is intention to continue the monitoring after the NCP project has ended. These projects illustrate how longer-term studies evolve over time and develop into successful ongoing collaborations with Indigenous communities; interpretations of Hg concentrations in wildlife and Hg dynamics in the environment are informed by IK, new questions and variables are identified and considered. This is also the case in reference to the annual Hg monitoring conducted from trout (*Salvelinus alpinus*) in Laberge and Kusawa lakes near Whitehorse, Yukon (Fig. 1, #9).

Human biomonitoring (2014–2018) was also initiated by Gwich'in, Dene and Métis communities in collaboration with university scientists to investigate human exposures to chemicals through the collection of blood, hair, and urine. Samples were analyzed for a variety of contaminants, including Hg, as well as nutrient biomarkers (e.g., omega-3 polyunsaturated fatty acid and selenium) (Fig. 1, #10) (Drysdale et al., 2021). Consultation between the university-based researchers and Indigenous communities shaped several aspects of the work plan, including the timing of the sample collections, local coordinator hiring plans, endpoint selection, participant inclusion criteria, and linkages to wildlife community-based monitoring programs (Ratelle et al., 2018a, 2018b). The project relied on IK, to align the research design with local priorities and guide the return of results and knowledge transfer. To facilitate communication of technical information among researchers and community members, terminology workshops were organized with local Indigenous organizations, and terms (e.g., contaminant and risk) were reviewed with First Nations Elders to discuss their meaning and translations. In addition to bridging the research work plan with IK, these discussions catalyzed the sharing of values and cross-cultural communication.

Besides the projects above, a multi-year study on spatial variability in Hg concentrations in food fish and freshwater lake ecosystems (e.g., water, sediment, invertebrates) is currently underway in the Dehcho Region. This multi-stakeholder, community-driven research project involves Dehcho

First Nations, as well as Ka'a'gee Tu, Jean Marie River, Deh Gah Gotie, Liidlii Kue, Sambaa K'e, and Pehdzeh Ki First Nations (Fig. 1, #11). Annual sampling occurs for 2 to 3 weeks each summer in wilderness camps and is conducted by a joint crew of university researchers and Indigenous Guardians (local community members employed as "eyes on the ground" in Indigenous territories), which fosters two-way knowledge exchange. Guardians are involved with every aspect of sample collection and field processing. Indigenous Knowledge informs which lakes are fished, how/when they are fished, what types of samples should be analyzed (e.g., smoked fish, fish guts, liver) and other variables that should be considered, such as beaver (*Castor canadensis*) activity in the catchment and presence of permafrost slumps. Indigenous Knowledge has also led to a community-led spin-off project on how fish growth rates could be stimulated by harvest. Results from projects are discussed annually in face-to-face meetings in the North, at which time priorities for the upcoming year are re-evaluated in response to community and harvester concerns.

Other projects in the Northwest Territories have investigated metal contamination of Yellowknife Bay (Great Slave Lake) from gold mining to address concerns from the Yellowknives Dene First Nation over contamination in local fish (2013–2015). Yellowknife Bay is an important water body for subsistence fishing, including for whitefish, which were being collected for a school lunch program (Chételat et al., 2017) (Fig. 1, #12). The community was involved in framing the questions of this project and participated in the collection of fish.

In the region of Great Slave Lake, contaminants in fish and fish health have been monitored since the 1990s with help from the communities of Fort Resolution, Lutsel K'e, and Hay River Reserve; most of this research has been conducted under the NCP. The earliest Hg work was with Deninu Kue First Nation at Fort Resolution, who had been concerned for many years of the impact of a decommissioned mine on metals in the lake (Fig. 1, #13). A study was therefore designed with the community to investigate metals in water and sediments as well as in fish offshore of the former mining site and predatory fish commonly consumed. Community members contributed to study design and participated in the sampling. Reports were produced and meetings held in the community to discuss findings (Evans et al., 1998). Fort Resolution continued to work with researchers and has developed several successful partnerships including community-based monitoring of water quality and specialized studies, including Hg, with academic partners (Carr et al., 2017; Baldwin et al., 2018). In the same region, the Lutsel K'e First Nation was concerned that the skinny (i.e., malnourished and thin) fish found in Stark Lake could be related to contaminants from the abandoned Stark Lake Exploration site, an exploratory uranium mine (Fig. 1, #14). Several studies were conducted in the period between 2003 and 2013 on lake trout provided by the community and fish were analyzed for contaminants and the issue of skinny fish investigated (Evans and Landels, 2015). Skinny walleye (*Sander vitreus*) have also been observed and investigated at Trout Lake (Fig. 1, #15). Observations from these studies, initiated by the community, revealed a potential food safety issue that informed public health advice.

Since 2010, the Tłı̨chǫ Aquatic Ecosystem Monitoring Program (TAEMP) in the Northwest Territories (NWT) has developed and implemented an aquatic ecosystem monitoring program of lakes important to the communities based on IK and science. The program has involved a rotating sampling through each of the four Tłı̨chǫ communities with studies designed to address questions as to whether the water is safe to drink and the fish safe to eat. A fish camp held on the land with Elders, youth and research scientists is the heart of this program. A detailed report is produced annually with results including Hg levels in fish and sediments, and data are provided to the territorial Health Department for assessment (NCP, 2018; TAEMP, 2019).

In the same region, Gwich'in and Inuvialuit knowledge holders from Aklavik, Fort McPherson, Inuvik, and Tsiigehtchic had been observing, over several decades, increases in the number of beavers and river otters (*Lontra canadensis*), alongside marked declines in muskrat densities, across much of the Mackenzie Delta (Fig. 1, #16). The Gwich'in Renewable Resources Board, the Gwich'in Renewable Resources Councils, and the Aklavik and Inuvik Hunters and Trappers Committees then engaged researchers to study potential drivers of change, including Hg. Project planning and reporting were conducted within the established decision-making frameworks of partner organizations (e.g., the Gwich'in Renewable Resources Board and local Renewable Resource Councils) and involved regular face-to-face meetings between scientists and IK holders (see Hovel et al., 2020). Indigenous Knowledge holders were active in the selection of sites, collection of samples, trapping of animals and recording of observations. Fieldwork was conducted with a multi-generational team of IK holders typically composed of youths, adults, and Elders; IK was recorded each day through a daily camp log. This project facilitated the sharing of both scientific and IK with the broader community through activities at local schools and college campuses including giving talks and leading activities (e.g., animal dissections). A contaminant study was also initiated by a Gwich'in fisheries biologist in Inuvik in collaboration with federal researchers, to address concerns about the quality of loche (burbot; *Lota lota*) livers in different channels of the Mackenzie River delta (Fig. 1, #17). It was found that the fish with the poorest quality liver were older fish with higher parasite loads. Results also showed that traditional (visual examination by skilled fishers with decades of experience) methods effectively assessed the quality of livers by identifying the most nutritious (high in fat) and safest (low parasite load) livers. This highlights the importance and value of linking IK into scientific studies.

In the Inuvialuit Settlement Region (ISR), the federal government and the FJMC have developed conservation management efforts informed by the long-term Beluga Harvest Monitoring program (1980–present) through partnerships with Inuvialuit Hunters and Trappers Committees and local hunters. This program has been providing scientists access to beluga tissues and has allowed for contaminants measurements to be taken, including Hg (Fig. 1, #18) (McKinney et al., 2022; Morris et al., 2022a). The program has evolved over 40 years, and is effective at responding to community questions, meeting management needs, and ensuring that scientific investigations can be carried out, bringing together a community of knowledge holders to collaborate on the study of beluga health (Loseto et al., 2018). Fig. 2 illustrates the integrated nature of the core beluga monitoring program in the ISR, which not only covers contaminants, but many other aspects that are related to beluga health. This highlights the holistic approach taken by the program which is guided by IK and IK holders are key to the program's investigatory aims. As the program conducted research, gained knowledge and highlighted questions with regards to beluga, the need to identify knowledge gaps and set priorities.

In this on-going monitoring, Indigenous communities are part of the planning, field crew, sometimes participate in lab analyses, and often are part of the dissemination of results at meetings and conferences. The documentation of IK in the beluga health program was formalized through the creation of IK indicators for long-term beluga monitoring (Ostertag et al., 2018); other projects as part of the program also document IK on hunting, on the processing of beluga, as well as on the impacts of climate change on beluga subsistence in Tuktoyaktuk (Waugh et al., 2018). Most recently, a project was developed based on outcomes from the 2016 Beluga Summit to address the decline of the beluga harvest in Aklavik, specifically to look at environmental and socio-economic changes (Worden et al., 2020). Moreover, the community of Paulatuk, which began regularly hunting beluga whales in the 1990s, initiated its own on beluga health monitoring in 2011, which has been maintained since.

Mercury was also investigated in water, food webs and fish of the Husky Lakes from the ISR in collaboration with the Tuktoyaktuk and Inuvik communities (2012 – 2013). Interaction with both communities through public meetings, interviews, and expert consultations helped design the study and sampling. Results indicated higher Hg levels in apex species and differences in fish levels between lakes (Fig. 1, #19) (Gantner and Gareis, 2013).

3.2.2. Nunavut

Multiple Hg studies utilizing IK have taken place in Nunavut, the largest region of Inuit Nunangat (the homeland of Inuit in Canada). Hunters and Trappers organizations from the Kivalliq region helped identify potential

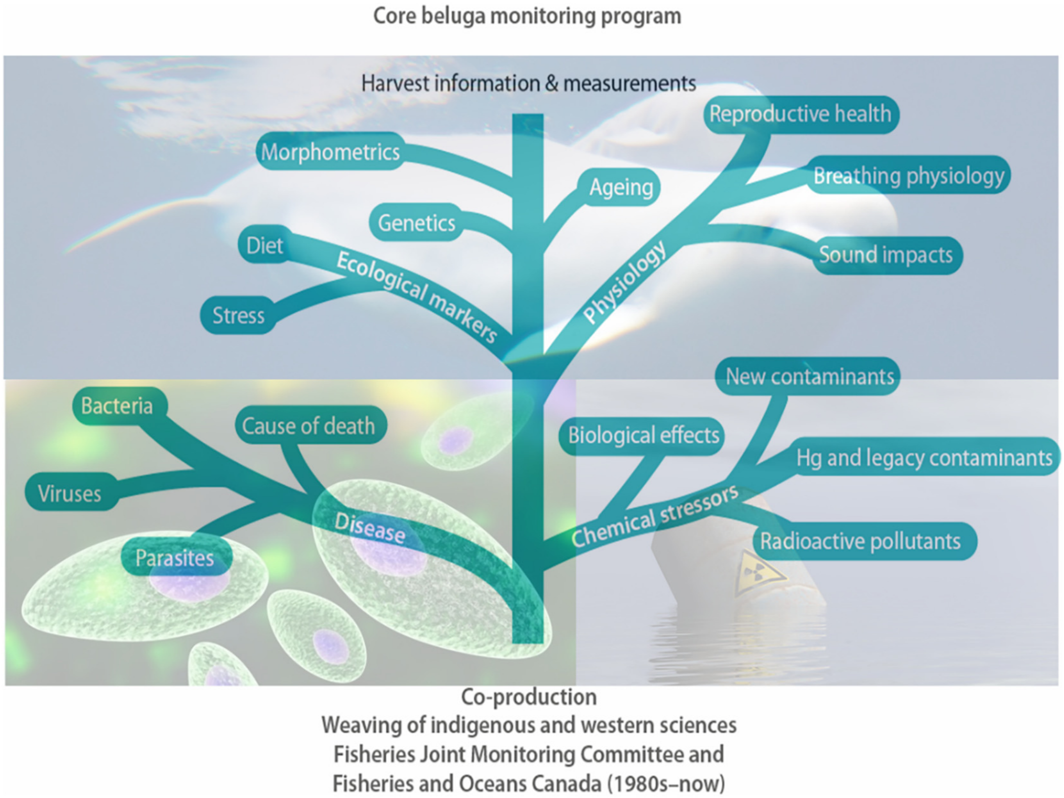


Fig. 2. The collaborative beluga harvest and health monitoring and research program (ISR, Canada) as an example of co-production of knowledge. The trunk of the tree is maintained by communities, their knowledge, their harvest programs and their priorities that has resulted in numerous branches of new knowledge and research focused on health, some representing short projects addressing a question and others being long term monitoring such as contaminants as part of food security and safety priorities. (Modified from Loseto et al., 2018).

dietary sources of Hg to caribou and supported sampling of lichen, mushrooms and seaweed around four different communities (Fig. 1, #20).

At Cambridge Bay on Victoria Island, researchers began working in partnership with the Hunters and Trappers Organization and university researchers in 2014 on Hg in lakes, including Greiner Lake (Grosbois et al., 2022), following report by Swanson et al. (2011) of high Hg concentrations in some Nunavut lake trout populations. Community members were involved in fish collections. Lake trout and some lake whitefish were found to have much higher Hg concentrations than sea run char; results were shared with the Nunavut Health Department and with the community (Evans and Muir, 2018).

Another example of a community-driven study on contaminants (including Hg) was based on fish favored by residents of Gjoa Haven on King William Island (Fig. 1, #21). This need was driven by the fact that Hg concentrations were measured in sea run char in 2004 but concentrations were not measured in other important subsidence fishes (Chételat et al., 2015; Evans et al., 2015). Gjoa Haven residents wanted a variety of regularly consumed fish species to be examined and results available in a timely way. The community then initiated a contaminants project associated with a larger food security initiative and a potential sustainable commercial fishery. While not all the activities were specifically undertaken for the contaminants project, they helped to inform it. The Gjoa Haven Hunters and Trappers Association and community Elders mapped out water bodies to be fished. Structured interviews were conducted with Elders, food preparers and youth during workshops held in the community and on the land. Elder-youth field trips were also organized, and information was sought from women working in a community prenatal group and other local food programs. The IK information gathered, including favorite fishing sites and animal harvest regions, was mapped onto an online Atlas (see Schott et al., 2019). The contaminant aspect of the project involved the training of community youth to collect biological data on fish as well as to perform tissue dissection. In person biannual reports on the progress of the project were presented to the Hunter and Trappers Association and at community meetings. All data has been placed in the Polar Data Catalogue where it is freely available, and posters and manuscripts for scientific audiences include the former chair of the Hunters and Trappers Association as a co-author (e.g., Walker et al., 2020; Koch et al., 2021).

In another Nunavut region, a long-term Hg monitoring program of seabird eggs and bird carcasses from Resolute Bay (Prince Leopold Island) and Coral Harbor (Coats Island; Akpatordjuark) has been ongoing since 1994 (Fig. 1, #22). This project was initiated by the NCP based on concerns expressed by communities on high levels of contaminants in country foods (Morris et al., 2022a; Chételat et al., 2022; McKinney et al., 2022). Country foods, or traditional Inuit foods, may include game meats, fish, migratory birds, eggs and other foraged foods from the land and the sea. Annual meetings and involvement of the Sulukvaut Area Co-Management Committee and the Hunters and Trappers Association continuously inform experimental design and field collections. Some community members expressed initial concerns that field research activities might be disruptive to seabird colonies. The continued communication efforts by the research team led to a better understanding of the project and ultimately helped to secure majority community support for continued research on Prince Leopold Island. Capacity-building, field training during sampling periods and opportunities for community members to participate are routinely part of the program, and have led to Inuit research assistants providing training and mentoring to other local research assistants.

As a notable example of the study of contaminants, including Hg, in land mammals from Nunavut, the Qamanirjuaq caribou herd around Arviat has been sampled and their tissues analyzed for contaminants. The Beverly and Qamanirjuaq Caribou Management Board and Kivalliq Hunters and Trappers Organizations provide input and guidance for the evolution of this long-term monitoring study (Morris et al., 2022a; McKinney et al., 2022).

In the marine environment, a project investigating heavy metals, including Hg, and various health parameters in ringed seals (*Pusa hispida*) from Iqaluit and Pond Inlet was conducted in the period 2017 to 2019 (Fig. 1, #23). Associated research was done under NCP funding and co-led by an Inuit graduate student in Iqaluit, Nunavut. In Pond Inlet, narwhals (*Monodon monoceros*) were also included, and local hunters were contracted to keep a channel of communication between the researchers and community members. Surveys were also done in Iqaluit (and will be done in Pond Inlet) to investigate local concerns on ringed seal health, to define parameters of seal health to be measured by hunters, to assess trends of health over time and to explore future directions of seal research. Since the project was run by local researchers, access to the research team was open and given the size of the community and pre-established relations with all the local hunters, conversation flowed openly in-person and questions were swiftly answered. The local HTO was kept up to date by regular visits to the office in-person, as was the Nunavut Research Institute, and public as a whole.

Mercury has also been monitored since 1982 in polar bear tissues harvested by Inuit hunters from western and southern Hudson Bay (Fig. 1, #24). Since 2007, Hg in polar bear liver has been measured on an annual basis (Morris et al., 2022b). Recently, Hg monitoring of Hudson Bay polar bears, along with bears in the Kivalliq region, has included assessments of the trends of ecological and physical variables related to climate change (e.g., temperature and sea-ice conditions) and their relationships to changes in underlying food-web structure changing contaminant levels in bears (Morris et al., 2022a; McKinney et al., 2022). Key information provided by the hunters include behavior, foraging ecology, body condition and the breeding of bears. This collaborative sampling between communities and scientists has also allowed the investigation of the biological effects of Hg in bears from western Hudson Bay and, additionally, in bears from Baffin Bay.

As an example of a project which took a multi-species approach, Indigenous organizations from five communities (Sanikiluaq in Nunavut; Inukjuak, Umiujaq, Kuujjuaraapik in Nunavik; and Chisasibi in Eeyou Istchee) located on the shores of Hudson Bay and James Bay participated in a project from 2015 to 2018 on metal accumulation in the marine food web (Fig. 1, #25). Communities requested information on metal levels in marine wildlife to address concerns of contamination from hydroelectric reservoir releases into James Bay. Inuit or Cree hunters collected local marine animals in their traditional territory for Hg tissue analysis. The contaminants component was part of a larger Community-Driven Research Network, facilitated by the Arctic Eider Society, established to address challenges with regard to monitoring and environmental stewardship in the region based on coordination among and priorities set by Indigenous organizations.

3.2.3. Nunavik (Northern Québec)

In the northern region of Québec, metal bioaccumulation was investigated in country food from Kuujjuaraapik (2013–2015) to assess if levels of Hg had changed 20 years after initial Hg measurements had been made for an environmental assessment of a large-scale hydroelectric project (Fig. 1, #26). This study was a collaboration between a local Inuit organization (the Sakkuq Landholding Corporation), government scientists and Inuit hunters, who collected relevant marine animals, terrestrial wildlife and freshwater fish for tissue analysis within their traditional territory.

In 2016, a project named *Imalirijiit* (those who study water; Gérin-Lajoie et al., 2018) was launched by university researchers and the Inuit community of Kangiqsualujjuaq to build a community-based monitoring program in the George River Basin (Fig. 1, #27). Community members chose to monitor the environmental quality of the lower George River because of mining development planned upriver from the community. This ongoing project assesses trace elements in river water, sediment, lichen, fish, birds and seals. Indigenous Knowledge is used to select sampling stations as well as to document Inuit land use, and changes to plant and animal ecology, the river and the landscape. At the heart of this collaborative project is a science land camp program co-organized with the Youth Committee, which involves youth, Elders, knowledge holders and researchers. Participating Elders and local guides/hunters have been interviewed with the help of interpreters. Community members, including youth participants, have been involved each year in presenting the project at scientific and regional meetings and a short documentary was created about *Imalirijiit* to share the collaborative approach and project goals.

When it comes to studies of human health, maternal exposure to Hg and methylmercury (MeHg), as well as other contaminants and nutrients, from country food have also been monitored in Nunavik since 1992. In 2016, the biomonitoring project was given the formal title *Nutaratsaliit Qanuingisiarningit Niqituinnanut* (Pregnancy wellness with country food) (Fig. 1, #28). Across the fourteen communities of Nunavik, blood and hair samples from Inuit pregnant women have been analyzed and MeHg intake estimated using food frequency questionnaires as well as existing Hg/MeHg data in wildlife. Information on food security, anemia, iron deficiency and awareness of public health messages was also documented. Midwives have guided the project from the outset and an open and continuous dialogue between academic researchers, the Nunavik Regional Board of Health and Social Services (NRBHSS), the Nunavik Nutrition and Health Committee (NNHC) and communities has led to the evolution of this ongoing project. Through time, knowledge has also been shared and discussed with Nunavik caregivers, pregnant women, grandmothers and hunters to promote healthy pregnancies and better child health through country food consumption; the AMAP 2021 Human Health Assessment has more detailed information on this study, including the Hg data (AMAP, 2021b).

As a further example of human health monitoring activities involving Indigenous Perspectives and IK, in 2017, a major population health survey, the *Qanuilirpitaa?* How are we now? 2017, was conducted in all Nunavik communities and involved the collection, analysis and dissemination of information on the health status of Nunavimmiut, including their exposure to several contaminants, as well as their food consumption and nutrition status. The work was guided by the *Qanuilirpitaa?* Steering Committee and coordinated by the NRBHSS, which ensured the political and administrative legitimacy of the process. The general objective of this survey was to provide an up-to-date portrait of the health status of Nunavimmiut as a follow-up study on the health of participants since the last survey in 2004 (NRBHSS, 2004). A Data Management Committee is responsible for overseeing the management of the data and biological samples and has the mandate to discuss/co-interpret the results generated by the survey. Values and principles such as empowerment and self-determination, respect, value, relevance and usefulness, trust, transparency, engagement, scientific rigor and pragmatism are at the core of this project (see also AMAP, 2021a, b).

3.2.4. Nunatsiavut (Labrador)

In Nunatsiavut, ringed seals, which are an important country food in several communities, have been the subject of several studies led in collaboration between communities, the regional government and scientists. Long-term monitoring of Hg in ringed seals from Nain, and other regions from Inuit Nunangat, such as the NWT (Sachs Harbour) and Nunavut (Resolute Bay and Arviat), has been ongoing since the 1990s (Fig. 1, #29) (Morris et al., 2022a; McKinney et al., 2022). This project has relied on local hunters to collect ringed seal samples over time (Houde et al., 2020). Since 2016, outreach activities in communities involved in the project have been integrated to this monitoring work (Henri et al. Submitted). This aspect of the project addressed a shared interest among Inuit and scientific researchers in enhancing communications and community capacity building related to contaminant research. Workshops conducted in northern schools across the Inuit Nunangat (i.e., Resolute and Arviat, NU; Sachs Harbour, NWT) provided opportunities for Inuit Elders to share their knowledge on seals with students and researchers. Northern college students and community-based organizations have been involved in these activities to increase capacity and training among Northerners as well as to ensure best practices for communicating contaminant research (Henri et al. Submitted).

Mercury contamination and associated health effects in ringed seals and their food web has also been investigated in the region (Fig. 1, #30). This project was initiated in 2006 to address Inuit concerns about the impacts of climate change, modernization, and contaminants on the health of marine ecosystems and communities in the region. Inuit have been involved in all aspects of the program, including the direction of research, design, and planning of projects, field and reporting of results. A goal of this research program builds on existing capacity between Inuit and researchers (thereby enhancing capacity sharing) and integrates a training component for Inuit students (kANGIDLUASUk summer student program). The scientific study on Hg levels in ringed seals and diet and health indices has been complemented by IK, which was collected from local hunters and documented to improve the understanding of ecosystem changes that may be related to or influencing Hg and other contaminant trends in Nunatsiavut ringed seals (CACAR III 2012). The ringed seal health component is co-led by Inuit and all sample collections are carried out by community members. This research was initiated in support of priority concerns of Inuit along the coast and is supporting a marine planning initiative ("Imappivut"; Our Oceans) that is working with communities to gather knowledge about areas, uses, and activities that have ecological, social, cultural and economic importance to Labrador Inuit. This research program aims to build capacity by providing opportunities for Inuit beneficiaries to lead or contribute to the research in support of marine protection and management and to develop skills with which to conduct long-term marine monitoring in the region.

Another research project in the same region was initiated in 2012 due to concerns of communities and the Nunatsiavut Government about the levels of MeHg in Lake Melville following the hydroelectric power development on the Churchill River (Fig. 1, #31). This project was co-led, designed and carried out by scientists, the Nunatsiavut Government, the Nunatsiavut Research Centre, and the communities of Happy Valley-Goose Bay, Northwest River and Rigolet. The objectives included community-led food web sample collections through fishing and hunting activities, dietary surveys across the different communities and sampling of community members for Hg in hair (Schartup et al., 2015; Calder et al., 2016; Durkalec et al., 2016a, 2016b). Results showed that there would be increases in MeHg levels in fish, ringed seals and Indigenous Peoples who consume them, as a result of the hydroelectric development. Results spurned an independent review of potential measures that could protect the health of the Indigenous and local populations from the effects of MeHg related to hydro development. More vigorous monitoring is now being carried by the Government of Newfoundland and Labrador to assess potentially changing MeHg levels in Lake Melville water and biota (https://www.gov.nl.ca/ecc/methylmercury-mrf/). Training is provided on all aspects of sample collection to increase scientific capacity in the region. Annual community meetings are organized to share information and obtain feedback and input from the community; these communications continued following the reservoir flooding carried out in 2019.

Finally, a long-term Hg monitoring program in the muscle tissue of Arctic char from Nain and Saglek has been on-going since 1997 and 2014, respectively (NCP, 2018). This regionally-led community-based monitoring program has aimed to build capacity in the region while addressing contaminant concerns of Labrador Inuit. The project supports recommendations from the 2008 Inuit Health Survey (Egeland, 2010) and the ArcticNet IRIS 4 report (Allard and Lemay, 2012) concerning Arctic char, while supporting knowledge transmission between youth, harvesters and Nunatsiavut Government staff. To further build capacity and enhance training, knowledge exchanges between Nunatsiavut Government employees and federal scientists through training has helped towards a better understanding of the research process and enabled clear communication with community members. This research has also recently expanded to assess the spatiotemporal patterns of Arctic char feeding behavior and Hg accumulation in connection with sea ice and other environmental parameters between 2007 and present.

3.3. Greenland

In Greenland, sampling of biota for Hg research (and other contaminants) has been conducted with the help of Inuit hunters since the 1970s (Fig. 1, #32 to 37). The reason for initiating work on contaminants in traditional foods was, and still is, related to human health in addition to the health of Greenland's wildlife. The Ittoqqortoormiit (Scoresby Sound) polar bears project, conducted by academic scientists from Denmark in collaboration with the Greenland Institute of Natural Resources (Nuuk, Greenland), is one of the longest time series available for wildlife in the Arctic spanning from 1983 to present; these 38 years of contaminants data were made possible because of the long-term collaboration with the East Greenland Inuit population. Wildlife and fish sampling was also initiated under the Heavy Metals in the Greenland Environment program (1985–1988). Moreover, since 1995, long-term monitoring of Hg has been ongoing under the Greenland CORE program including samples from polar bears, ringed seals, black guillemots (*Cepphus grille*), sculpins (*Myoxocephalus* spp.) and arctic char. Narwhals, beluga, killer whales (*Orcinus orca*), walrus, harp seals (*Pagophilus groenlandicus*), hooded seals (*Cystophora cristata*), bearded seals (*Erighnatus barbatus*), seabirds, fish species and musk oxen (*Ovibus moschatus*) have also been collected in collaboration with the Inuit population (Morris et al., 2022a; McKinney et al., 2022). For the species with hunting quotas, only full-time hunters were allowed to collect the animals; it has been customary for scientists to conduct the sampling in close and efficient collaboration with the skilled Greenlandic Inuit hunters. Meetings have been regularly organized with Inuit hunters over the course of undertaking field work and presenting results. Moreover, the scientists involved are in year-round contact with key hunters enabling the exchange of mutual information on relevant issues regarding the hunts and science information including contaminant exposure and health issues.

During these projects, Greenland hunters have provided information for the timing of the hunts, the migration patterns of animals and climate related changes in both East and West Greenland (see Glahder, 1995; Sandell et al., 2001; Born et al., 2011). Interviews were also conducted with Greenland hunters on the health condition of polar bears in East Greenland, this information was analyzed in relationship with to high contaminants loads in bears (Dietz et al., 2001). Finally, human Hg exposure was estimated through analysis of information provided by hunters to the Greenlandic Hunting Statistics (1993–2013) for the Avanersuaq, Ittoqqortoormiit, and Nuuk regions; the amount of Hg entering the local diet has been estimated by Dietz et al. (2018a, 2018b) also described in this Special Issue (Basu et al., 2022).

3.4. Sweden

Very few national programs supporting the community-based monitoring of contaminants exist in Sweden. In Eurasian North, the Snowchange Cooperative has been conducting community-based monitoring since 2000 and managing several projects that include aspects of Hg contamination. Their work has included weather, ecological change, documentation of fishing/hunting diaries, oral history documentation, ecological mapping, satellite imaging and contaminant data interpretation as well as community workshops and conferences (Syrjämäki and Mustonen, 2013).

Some of the main local sources of Hg contamination in Sweden have included construction of large-scale hydropower stations (e.g., at Luleå) as well as industrial mining and forestry. These anthropogenic activities have been a cause of concern for local Indigenous communities for decades. Impact assessments of hydropower development and forestry practices on Sámi communities were conducted between 2003 and 2013 in the Jokkmokk region (Fig. 1, #38) in the form of a literature review of national Hg data alongside interviews with community members (Syrjämäki and Mustonen, 2013). Sámi leaders were also invited to assess the present questions of Hg in the area (Mikaelsson, 2020). Overall, Sámi knowledge holders reported considerable negative impacts due to environmental destruction and water regulation, in particular to their fisheries and reindeer grazing grounds (see SM Case study 1). Recent reports of Hg concentrations in thawing permafrost (Schuster et al., 2018) have also been of concern to the Sámi within the Lule River basin (Mikaelsson and Mustonen, 2020).

3.5. Finland

Community-based monitoring of Hg is still very novel and a pioneer field of assessment in Finland. The Snowchange Cooperative has led many efforts on the Hg contamination and impacts on communities through long-term monitoring activities across the country. Monitoring was initiated on the request of the Saami Council and the local Sámi stakeholders in the early 2000s. In the Finnish-Karelian communities of Koitajoki, Hg has been a public concern since the 1970s. For each project, consultations are done with the communities and heads of village, the Saami Parliament, or the Saami Council regional representatives and workshops are organized to present the proposed research. Then, a Saami or a Finnish village coordinator, usually appointed by the community, works with Snowchange to create conditions for collaboration and co-production of knowledge. Information is shared among partners prior to presentation at public workshops and events.

In the Finnish Arctic, the impacts of Hg contamination in relation to hydropower development and forestry practices on Sámi communities and wildlife were investigated around the Lokka and Porttipahta reservoirs (Lapland) between 2000 and 2010 (Fig. 1, #39). These reservoirs, constructed in the 1960s and 1970s, significantly impacted and/or displaced Sámi and Finnish communities and altered, or in some cases even destroyed, the traditional economies and cultures of reindeer herding and hunting as well as fisheries. The potential Hg sources, impacts of contamination and concerns of the Sámi communities were identified by conducting a national literature review as well as with IK through community visits and community-based observation, by using oral histories and by conducting contemporary diary reviews (Mustonen et al., 2011; Murtomäki, 2020). During the establishment of the reservoirs, massive areas (spanning ~417 km^2) were clearcut and treated with Agent Orange (SM Case study 2). In the 1970s, public warnings about consuming fish in the Vuotso area were issued due to increased Hg levels (up to 0.99 mg/kg in northern pike; *Esox lucius*), but Sámi continued to consume the local fish. In other cases, public debate on possible Hg contamination of fish led to anecdotal story telling about risk and risk avoidance: for instance, hanging large pike upside down in freezing temperatures was believed to transfer Hg into the fish head, which could then be cut off and, in this way, the Hg would be removed (Murtomäki, 2020). While this story can be understood also as a means by which the local peoples form relations to modern issues through anecdotes, these stories and narratives help provide a local perspective on how communities have responded to the rapid and often negative shifts in the state of the natural environment in the present era without having means or mechanisms to influence top-down decision making.

Mercury measurements in the reservoirs in the early 2000s indicated that levels in humans and fish were lower than in the 1970s (with max. levels in certain fish at 0.99 mg/kg in 1970 to 0.34 mg/kg in 2012; see summary in Alanne et al., 2014). Similar concerns led to a community-based observation network for the Koitajoki waterway (part of the Vuoksi watershed in North Karelia, Finland and Republic of Karelia in Russia) (Fig. 1, #40). The network was established in 2016, with early oral history documentation starting from 2001. The work used traditional knowledge (as per definition in Textbox 9.2, some of the knowledge holders are not officially recognized as Indigenous Peoples and belong to minority, non-indigenous populations that possess similar knowledge) to detect and contextualize open questions regarding boreal river systems and Hg. The main data for this case study were derived from the Finnish side of Koitajoki (SM Case study 3). Causes of the Hg increases in the ecosystem included the increased activities of industrial plants (e.g., pulp and paper mills; Wahlström et al., 1996), peat production, forestry management and site-specific gold mining (Mustonen and Mustonen, 2018; Albrecht, 2019). Additional local concerns arose from samples that were taken by regional authorities and researchers from local people in 2016 and 2017 to investigate Hg levels but the results have not yet been reported back (Mustonen and Mustonen, 2018). Sampling of predator fish in 2014 in areas close to the hydroelectric station has also found high Hg levels in tissues (e.g., 0.74 mg/kg in young pike; Albrecht, 2019). Traditional river seining which removes organic matter and large-scale catchment restoration could help reduce Hg loading, or at minimum maintain and expand traditional knowledge observations. Community-based monitoring efforts will constitute a central element of this restoration work in the near future.

3.6. Russia

As is the case in other Arctic regions, the main local sources of Hg in Russia can be attributed to coal combustion, mining and the production of metals (e.g., nickel, zinc and gold). Mercury can also be released from waste management and industries. However, while Hg and other contaminants have received international attention in recent decades, Fennoscandia and the Eurasian North (i.e., the Russian Arctic) have been less studied, especially in the context of IK and local knowledge. This knowledge is of special importance in the Russian Arctic due to the role and scope of Soviet-era industrial activity (from around 1917 to 1991, with significant increases in activity in the 1930s) as well as legacy industrial releases that constitute environmental gaps in knowledge across the region.

In the Ponoi River catchment (Murmansk Region), observations of the impacts of Soviet chemical legacies on the communities of Krasnochelye, Kanevka and Ivanovka and on the Sámi and Komi communities as well as wildlife have been assessed (Fig. 1, #41). During the Soviet era, the villages of Krasnochelye and the secret military installations may have been source of Hg release in the environment. Mercury levels were therefore investigated in the villages of Ponoi and adjacent Sosnovka between 2005 and 2020 using scientific data (Soviet and Russian observational data combined with a literature survey; Velichkin et al., 2013) and a community-based network (oral histories and community-based observation; see more in Johnson et al., 2015). Community-based observations were aimed at reconstructing pollution events, assessing convergence or divergence between scientific and historical data, and recording expertise from the local populations (see SM Case study 4). The Ponoi example is important in yielding past environmental data for understanding the present, especially in the context of Hg monitoring and how it ultimately affects northern Indigenous communities, their health and surrounding environment. Oral history can be useful in identifying undeclared pollution events and directing future CBM efforts and remediation. Moreover, IK and local knowledge have often been critical in a context of (presumably) limited flow of government information that might have helped protect both community and ecological health. For example, several pollution events were reported, these included the dumping of chemicals, releases from mining and uranium sites, as well as diesel spills. However, data were preliminary, and further work carried out in the period 2020 to 2021 has aimed to include pike and burbot sampling to determine Hg levels in different areas of Ponoi (unpublished data).

Similar work has been done in the Kolyma River catchment to support the assessment of Hg impacts on the communities in the region as well as their environment (Fig. 1, #42). Kolyma is the home of Indigenous Peoples of Eastern and Northeastern Siberia, including the Even, Chukchi, Evenki, Koryak and the Yukaghir. Kolyma basin has been affected by hydroelectric dams, artisanal and small-scale gold mining (ASGM; where Hg may be used to separate gold particles from sediment) and industrial mining operations that have sourced Hg to the river for a century; present changes include sourcing from climate change impacts including permafrost melt and floods (Eagles-Smith et al., 2018). Community voices from the region were documented between 2005 and 2020 and combined with remote sensing/satellite imagery, geographical analysis and regional governmental data to investigate the drivers of Hg contamination, since Hg levels have been found to be quite high. For example, a scientific study reported Hg levels of up to 1.8 mg/kg in perch (4–6 years old) in mid-Kolyma (Tiaptirgianov, 2017). Community-based observations have also reported ecosystem impacts (e.g., changes in water color and temperature, fish migration and the reduction or collapse of fish stocks), as well as direct (e.g., changes in fish smell, taste and health) and indirect (e.g. ethical and cultural) impacts associated with the environmental contamination by Hg on Kolyma and neighboring streams (SM Case study 5 and Mustonen and Shadrin, 2021).

Observations of the impact of modern-day ASGM on the communities of Evenki reindeer herders were further done in the Iyengra River basin (Eastern Siberia) (Fig. 1, #43). Sixteen years of CBM work with the Evenki has resulted in the mapping of gold mining sites and descriptions of the impacts on reindeer and wildlife health, such as the loss of fisheries and access to clean waters, alterations to waterways (depth, water color, and accessibility) and the ethno-psychological impacts of alterations to the Evenki home area (SM Case study 6). Available chemical data supported IK in defining the poor water quality of the Iyengra River. However, the lack of information on the use and release of Hg by mines led to a large divergence between reported impacts of artisanal mining operations and impact observations made by the Evenki. This project demonstrated the use of communal mapping of problematic sites and methods of negotiating environmental issues by those who live nature-based nomadic lifestyles, particularly in relation with Hg contamination and major river contamination in an absence of state controls on pollution events. Summary results of the land use changes have been released as a part of the Evenki Atlas (ELOKA and Snowchange, 2020).

4. Indigenous contributions to the understanding of Hg contamination in the Arctic

In recent years, Indigenous communities often have chosen to participate in, or initiate contaminant research projects because they were, or are, worried about the health of the ecosystem and safety of their traditional country foods. During the early stages of contaminant research in the Arctic (i.e., starting in the late 1980's in Canada), the finding of high contaminant levels in the remote Arctic environment rattled researchers and led to fear-inducing communication and messages directed towards to public (see review by Furgal et al., 2005 and chapters on risk communication in AMAP Human Health Assessments: AMAP, 2015, 2021b). Arctic Indigenous Peoples were instrumental in developing a shift in the perception and understanding of contaminant risk associated with a diet consisting of traditional country foods compared to the many benefits. This shift caused a stronger emphasis of research and communication around health, nutritional and cultural benefits associated with traditional country foods, instead of focusing on contaminant risk alone, and increasing the overall understanding of linkages between the importance of the traditional diet and well-being (e.g., Kinloch et al., 1992, Kuhnlein et al., 2000, Blanchet and Rochette, 2008).

Moreover, the various projects described above illustrate the important contributions that Indigenous communities and knowledge holders have made to our broader understanding of Hg contamination in the Arctic. Specific examples below highlight where IK has informed the interpretation of contaminants data and/or acted as a driving force through various research projects on contaminants:

1) In fish research in Nunavut, scientists expected to find moderate levels of Hg in Lake Whitefish (*Coregonus clupeaformis*) collected around Gjoa Haven due to their freshwater habitat, but IK indicated that the whitefish migrated to the sea to feed after the ice was out. This valuable information helped explain why levels of Hg were, in fact, lower than might be expected in this species (Koch et al., 2021).
2) Caribou research results indicated that individuals from the Qamanirjuaq herd had higher Hg concentrations than other Arctic caribou. Caribou usually get most of their Hg from lichens, but local Elders described the Qamanirjuaq caribou eating seaweed from the seashore. Since seaweed is known to accumulate metals, it was hypothesized that the caribou may be getting additional Hg from this source. Consequently, Inuit community members interviewed Elders about caribou diets; vegetation samples were collected in each of the communities and Hg was measured in lichens, mushrooms and seaweed from communities in the Kivalliq region of Nunavut. Ultimately, Hg concentrations were however found to be lower in seaweed than in mushrooms and lichens, and more research will be necessary to determine the reason for the difference (https://www.northerncaribou.ca/).
3) In the Northwest Territories, Délı̨nę fishermen have observed different types of lake trout in Great Bear Lake; fish living in different regions of the lake had different food in their stomachs and different appearances. These observations led to collaborative studies with researchers to investigate Hg concentrations in relation to feeding ecology, habitat and age of fish. While Hg concentrations differed between ecotypes, these fish also differed in their size and growth rates all of which were related to Hg concentrations. Preliminary results indicate that bottom-feeding fish seemed to have the highest Hg concentrations on average for a given length (M. Evans and L. Chavarie, personal communication).
4) Local concerns about skinny fish and low quality of burbot liver that were found in lakes and rivers in close proximity to communities have led to several studies on liver quality and contaminants including Hg in NWT and the Yukon (Chételat et al., 2015; Cott et al., 2018). Observations made by the community have led to the investigation of condition factors (including growth rate) of fish during Hg spatial and temporal trend studies to try explain the condition of skinny fish and help established guidance for consumption.
5) Research in Nunavik showed that beluga *mattaaq* (skin) had high levels of selenoneine, a compound that may be protective against negative Hg effects. Elevated levels of selenoneine were also found in the blood of Inuit from Nunavik, with mean selenoneine concentrations in women being two-fold higher compared to those in men (Little et al., 2019; Basu et al., 2022). When the scientists reported the findings, Inuit experts explained to them that these differences may have to do with the fact that only Inuit women eat the tail of the beluga (Little et al., 2019). Preliminary analysis of different parts of the beluga whales then revealed that in fact, selenoneine concentrations in the skin of the beluga tail are around twice as high compared to the skin from other areas (Little and Lemire pers. comm.).

Indigenous Knowledge can also provide invaluable ecological information that can elucidate effects of climate change, and other ecosystem changes, on contaminant levels in the Arctic environment, wildlife and peoples. For example, an extensive research project in Nunavik on beluga whales investigated IK and included (but was not limited to) migration, body condition, foraging ecology, predation, breeding, calving and behavior of animals (Breton-Honeyman et al., 2016). This knowledge on foraging ecology provides information on diet composition, complementary to other dietary approaches (e.g., stomach contents, stable isotopes and fatty acids), and on the seasonality of energy intake, important elements that can help understand beluga exposure to Hg and other contaminants.

Additionally, projects such as The Inuit Siku Atlas (ISIUOP, 2021) and The Indigenous Knowledge Social Network (SIKU; https://siku.org/#/about) allow for sharing of knowledge and observations by Inuit hunters in near-real time and incorporate a variety of culturally relevant tools that allow Inuit to interpret results using their own knowledge system (Heath et al., 2015; Arctic Eider Society, 2016). In several cases, these platforms include a mobile device application for use in the field and are used as a part of community-driven programs to systematically document IK and environmental observations, such as the body condition, behavior, diet, and ecology of animals and environmental conditions. Other initiatives, such as ArctiConnexion (https://arcticonnexion.ca/) and Ikaarvik (https://ikaarvik.org) are specifically engaging Inuit youth in research activities that involve studies in various natural sciences disciplines, including studies on climate change and contaminants (such as Hg).

In 2018, the Indigenous Sentinels Network (ISN) was launched in response to a growing need for practical and easy to implement community-based monitoring programs across Alaska and Canada. The focus of ISN is on effective real-time ecological monitoring by local community members (knowledge holders) and provides a flexible and customizable framework. This enables local resident observers and data collectors to record and monitor ecological phenomena and anomalies and analyze and communicate these data effectively to scientists, managers, other community members, stakeholders, and the general public. Communities determine the structure of their monitoring program and focal species or phenomena of concern or interest. For example, on St. Paul Island, the Ecosystem Conservation Office collects marine mammal samples since 1998 to assess body condition, diets and contaminant loads (including Hg) using standardized protocols that have been implemented in ISN mobile apps and online database. Such consistent long-term data collection efforts provide valuable information for local management efforts and thereby enhance the food security and resilience of tribal communities (Divine and Robson, 2020, and references therein).

More broadly, in the circumpolar Arctic, the utilization of IK in environmental research and monitoring and associated decision-making processes is an overarching mandate of the Arctic Council and associated working groups, such as AMAP, which are increasingly working towards this implementation (Arctic Council IPS, 2015; AMAP, 2019). Within AMAP, Arctic research on contaminants and human exposure in some countries (e.g., Canada and Greenland) would not be possible without the involvement of Indigenous Peoples. Active collaboration between Indigenous Peoples and scientists are also critical to core Arctic research that supports domestic and international chemical management initiatives.

Globally, the role played by Arctic Indigenous Peoples in the negotiations of international treaties, such as the Stockholm Convention on Persistent Organic Pollutants (POPs), or the Minamata Convention on Mercury, has been highlighted (Downie and Fenge, 2003; Fernández-Llamazares et al., 2020). In these cases, the involvement of Arctic Indigenous Peoples provided the human context to the contaminants issue and ensured that negotiations were not solely based on numbers, figures and economic interests. In particular, during the negotiations of the Minamata Convention, the Inuit Circumpolar Council (ICC) used results from NCP studies and AMAP assessments, such as graphs describing the exceedances of Hg guidelines by pregnant Inuit women in the circumpolar Arctic, as well as consumption advisories based on Hg in the traditional diet of Inuit in Nunavik and Nunavut, to highlight how Inuit are affected by Hg in the Arctic. The combined efforts by Arctic Indigenous Peoples and Arctic states during the negotiations led to the inclusion of Arctic Indigenous Peoples in the preamble of the two conventions. For instance, the Minamata Convention preamble states that parties to the convention have agreed to the articles therein “Noting the particular vulnerabilities of Arctic ecosystems and indigenous communities because of the biomagnification of Hg and contamination of traditional foods, and concerned about indigenous communities more generally with respect to the effects of Hg” (UNEP, 2019). The engagement of organizations and governments in United Nations conventions continues with the involvement of Arctic Indigenous Peoples' organizations (such as ICC) who are critical to the implementation of the conventions, in particular with regards to the effectiveness evaluation of the Minamata Convention on Mercury.

5. Overview of Indigenous perspectives and visions on contaminants research in the Arctic

There are several documents and publications that consider the ethical conduct of research (including contaminants research) with or by Indigenous Peoples, particularly in the Arctic, and provide guidance for conducting such research. The volume of peer-reviewed articles that call for “decolonizing science” to enable reconciliation (e.g., Jones et al., 2018; Wheeler et al., 2020; Wilson et al., 2020; Wong et al., 2020) is steadily increasing. Furthermore, some Arctic countries are recognizing the need for addressing the effects of historic colonization along with present-day biases and attitudes on research (e.g., Canada in 2019 and United Nations agencies, for instance within the UNESCO; Chan et al., 2020). However, this paper is not aiming to provide an exhaustive review on the topic based on peer-reviewed literature published in international journals and is not aiming to review government actions. Instead, it outlines some examples on perspectives and visions for the future that Indigenous Peoples have produced themselves and which are mostly not found in the published literature. For example, some guidance documents have been published by Indigenous organizations and provide useful information for scientists on how to ensure that any given research project meets Arctic Indigenous needs; such documents truly represent an Indigenous perspective. While it is out of the scope of this work to produce a comprehensive review of the Indigenous guidance documents available, a few of these are briefly introduced below and where applicable, some peer-reviewed articles written by Indigenous and non-Indigenous researchers are also referenced.

In the early 1990s, the Inuit Circumpolar Conference (now Inuit Circumpolar Council) developed its “Principles and Elements for a Comprehensive Arctic Policy” (ICC, 1992), which included “Principles and Elements on Northern Scientific Research” (updated in ICC's Inuit Arctic Policy; ICC, 2009). ICC continues to work on updating guidance for international research in Inuit Nunaat (the Inuit homelands across the Arctic), and has recently established protocols for ethical and equitable engagement (ICC 2022), which are supported by a synthesis report summarizing over 80 existing Inuit documents across Inuit Nunaat (ICC 2021). Together with the other Permanent Participants of the Arctic Council, they have also developed the Ottawa Indigenous Knowledge Principles on use of IK, co-production of knowledge and meaningful engagement of Indigenous Peoples in research (Permanent Participants, 2018). In Canada, the National Inuit organization, Inuit Tapiriit Kanatami (ITK), published the National Inuit Strategy on Research (ITK, 2018), which outlines the vision of Inuit self-determination in research in Inuit Nunangat, the context in which that vision is articulated, the objectives that must be set and the necessary actions that must be taken to achieve that vision. Moreover, the Assembly of First Nations developed a (not formally adopted) document entitled “First Nations Ethics Guide on Research and Aboriginal Traditional Knowledge” (Assembly of First Nations, 2011) while the Dene Nation published a report entitled “We Have Always Been Here. The Significance of Dene Knowledge” (Dene Nation and Assembly of First Nations, 2019), which describes in detail what Dene Knowledge is and provides recommendations for best practice when utilizing Dene Knowledge in decision-making. Many communities and regions in the North also have their own guidelines for research and the utilization of IK (see Dene Nation and Assembly of First Nations, 2019). Moreover, Ikaarvik youth recently published recommendations for science and Inuit Qaujimajatuqangit (Inuit Knowledge) to guide researchers in meaningful engagement with Inuit and the effective utilization of Inuit Knowledge (Pedersen et al., 2020). While not all these reports can be listed and described in detail here, some of the overall aspects include:

- History and cultural context

The historical, cultural and political contexts in which research is conducted should be understood and limitations in the understanding of Indigenous cultures and legacies of colonialism acknowledged (ITK, 2018; Schott et al., 2020). This understanding can help avoid negative consequences of research and power imbalance (Kral et al., 2011; Wiseman, 2015; Moon-Riley et al., 2019; Wong et al., 2020).

- Knowledge systems

Indigenous Knowledge is a holistic form of knowledge that is equally valid to scientific knowledge and should be respected as such. This requires transparency, mutual trust and equitable treatment of both knowledge forms. One general problem encountered with the utilization of IK are attempts to “incorporate” IK into “Western” scientific studies, leading to processes of labeling or defining the knowledge in fixed ways and thereby separating it from its context or process of developing. The result risks an exploitative situation by misinterpretation and misuse (Stevenson, 1996), failure to fully capture the underlying dynamic and flexible practice, as well as losing the depth of its sociocultural content (Dahl and Hansen, 2019). Similarly, when IK is rendered and reduced to scientific terms, it strips the knowledge of its full meaning and context. Indigenous Knowledge needs to be acknowledged and valued in the context of its original form (Dene Nation and Assembly of First Nations, 2019).

Moreover, IK is not confined to hunting and harvesting activities; it encompasses knowledge about the whole Arctic ecosystem, Indigenous cosmologies and is imbedded in Indigenous cultures and languages (Johnson et al., 2015; ICC, 2016; Dene Nation and Assembly of First Nations, 2019). IK should therefore be used to inform all steps of research, and knowledge holders need to be engaged in the analysis of research results which are based on their knowledge (Schott et al., 2020). Therefore, Indigenous Peoples generally prefer a co-production of knowledge approach, where knowledge holders and scientists work together to develop research questions, sampling approaches, discuss data analysis and interpretation, and communicate and disseminate results, all which is central in undertaking effective collaborative work. Scientists should not visit Arctic Indigenous communities with the intention to bring expertise but to listen, learn and work together with Indigenous colleagues. Some authors (Schott et al., 2020) call for a knowledge co-evolution process, where information is generated by joining knowledge systems in an inclusive and iterative way to facilitate community self-determination and promote cultural resilience. One central component in this process is the fostering of progress towards improved co-management and community-led research.

- *Ownership of information*

Indigenous partners have the right to control their intellectual property and data and should be recognized and credited for their knowledge (ICC, 2021, 2022; FNIGC, 2007; ITK, 2018). In 2002, the First Nations Information Governance Committee first published the principles on ownership, control, access and possession (OCAP®), which guide how information and data from Indigenous Peoples needs to be managed (FNIGC, 2007). Additionally, in many cases, 'western' scientific legal concepts of property rights may be insufficient when it comes to addressing Indigenous Knowledge, or the realities in Indigenous communities. Therefore, as outlined by ICC (2021), many Inuit organizations and/or communities have developed their own consent and contracting protocols, which need to be respected and followed.

- *Communication*

Communication is crucial and linguistic challenges need to be recognized. Not all IK holders are comfortable speaking English, and in some Inuit regions in Canada (such as Nunavut), Inuit have the right to use their language in full equality with the other official languages (English and French). Additionally, IK is often place-based, and words and concepts from Indigenous languages are not easily transmitted in or translated into English. When this is attempted, important meanings can become lost, and the embedded, situated, collaborative and performative nature of Indigenous concepts are erased (Dene Nation and Assembly of First Nations, 2019).

Communication is a particularly important part of research activities and allows for good knowledge exchange and informed decision making (Schott et al., 2020). Early and regular communication between partners helps to build trust, develop/discuss research questions, learn about timelines and priorities and address changes/roadblocks. The sharing of project information and results (via plain language summaries, pamphlets, newsletters, videos, interactive games, radio broadcast, social media, community events, or food sharing) is also key to keep the community informed (Henri et al., 2020).

Finally, a very specific aspect in communication on contaminant research is related to the cultural and nutritional importance of the traditional diet, benefits and possible health risks associated with exposure to contaminants (Furgal et al., 2005). There is a strong need that researchers make data on Hg levels freely available in public data bases, regularly communicate with their Indigenous and community partners, report results relevant to human health to local health authorities and, if needed, support the development of health risk assessments. However, human health-related messaging is the responsibility of public health officials and should not be independently developed and disseminated by academic research teams.

6. Conclusions

There are multiple examples of Hg research and monitoring conducted by or with Arctic Indigenous communities and/or regions. For this overview a greater number of projects have been found in Canada when compared to other Arctic countries. This is likely due to funding approach of federal programs such as the NCP in Canada. The NCP is managed by a committee consisting of federal and territorial government departments and representatives of Indigenous partner organizations. The process ensures Indigenous representatives are part of the decision-making, including a comprehensive review process, which contains a social-cultural review done by Indigenous regional committees. Correspondingly, the NCP has a specific portion of its funding dedicated to community-led contaminant research and Indigenous partnerships. Generally, the NCP has an annual budget of around 4.8 million Canadian dollars (example of funding for 2021–2022), and of that a certain amount is allocated to community-led contaminant research and Indigenous partnerships (in 2021–2022 around $300,000 and $900,000, respectively; see NCP, 2022). In addition, the NCP is well connected to and represented in AMAP, both by the Canadian government and Indigenous (Permanent Participant) representatives. We are not aware of other countries in the Arctic which provide similar, sustained support to Indigenous Peoples for participation in contaminant research, and community-based or community-led research on contaminants, which is then also connected to AMAP work. Hence, the dominance of Canadian community-based Hg monitoring projects described here is not surprising.

As was outlined in the present paper, research on contaminants and human exposure in several Arctic countries would be impossible without the involvement of Indigenous Peoples. The contribution of IK has greatly supported the understanding of Hg in the Arctic environment and has enriched research and monitoring on contaminants. Active collaboration between Indigenous Peoples and scientists is critical to core Arctic research that supports domestic and international chemicals management initiatives. Arctic Indigenous Peoples have played crucial roles in the development of global agreements on contaminants (e.g., the United Nations Minamata Convention on Mercury), and moving forward, they need to be involved in the implementation, including global monitoring efforts for the effectiveness evaluation of these agreements.

More generally as next steps for the research field, the research community needs to be aware that guidelines and protocols for ethical research exist which are developed by Indigenous regions, communities and organizations. These guidelines and protocols should be recognized before research projects are implemented and they need to be followed throughout the research activities. Important aspects that are emphasized by Indigenous Peoples and need to be realized in research and monitoring projects include understanding the historical and cultural contexts of research in the Arctic, Indigenous self-determination in research/monitoring; implementing knowledge co-production processes respecting IK; crediting ownership and primary sources of information; and emphasis on good communication practices.

The apparent gap of community-based Hg studies in many Arctic countries highlights that more sustained, long-term funding for community-driven monitoring and research programs in Arctic countries would be beneficial and assist in more research/monitoring capacity and the development of holistic knowledge. These activities should be well connected to circumpolar/international initiatives, such as AMAP, to ensure broader availability of the information and uptake in policy development on international scales. The establishment of collaborative processes and partnership/co-production approaches with scientists and Arctic Indigenous Peoples, using good communication practices and transparency in research activities, are key to the success of long-term research and monitoring activities in the Arctic.

CRediT authorship contribution statement

Magali Houde: Conceptualization, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Eva M. Krümmel:** Conceptualization, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Tero Mustonen:** Writing – original draft, Writing – review & editing. **Jeremy Brammer:** Writing – original draft. **Tanya M. Brown:** Writing – original draft. **John Chételat:** Writing – original draft. **Parnuna Egede Dahl:** Writing – review & editing. **Rune Dietz:** Writing – original draft, Writing – review & editing. **Marlene Evans:** Writing – original draft, Writing – review & editing. **Mary Gamberg:** Writing – original draft, Writing – review & editing. **Marie-Josée Gauthier:** Writing – review & editing. **José Gérin-Lajoie:** Writing – original draft. **Aviaja Lyberth Hauptmann:** Writing – review & editing. **Joel P. Heath:** Writing – original draft. **Dominique A. Henri:** Writing – original draft, Writing – review & editing. **Jane Kirk:** Writing – original draft. **Brian Laird:** Writing – original draft. **Mélanie Lemire:** Writing – original draft. **Ann E. Lennert:** Writing – review & editing. **Robert J. Letcher:** Writing – original draft, Writing – review & editing. **Sarah Lord:** Writing – original draft. **Lisa Loseto:** Writing – original draft, Writing – review & editing. **Gwyneth A. MacMillan:** Writing – original draft. **Stefan Mikaelsson:** Writing – original draft. **Edda A. Mutter:** Writing – review & editing. **Todd O'Hara:** Writing – original draft. **Sonja Ostertag:** Writing – original draft. **Martin Robards:** Writing – original draft, Writing – review & editing. **Vyacheslav Shadrin:** Writing – original draft. **Merran Smith:** Writing – review & editing. **Raphaela Stimmelmayr:** Writing – original draft, Writing – review & editing. **Enooyaq Sudlovenick:** Writing – original draft, Writing – review & editing. **Heidi Swanson:** Writing – original draft, Writing – review & editing. **Philippe J. Thomas:** Writing – original draft, Writing – review & editing. **Virginia K. Walker:** Writing – original draft, Writing – review & editing. **Alex Whiting:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Table S1. Definition of Indigenous and Local Knowledge as well as specific regional examples where terminology may be used differently. Table S2. Detailed information of selected community-based/led Hg monitoring and research activities involving Arctic Indigenous communities and regions illustrated in Fig. 1. Specific case studies from Eurasia are presented: 1. The River Lule: Heartland of the Swedish North; 2. Lokka and Porttipahta reservoirs, Lapland, Finland; 3. Koitajoki: Finnish-Russian border river; 4. Short case study: Linking environmental mercury data with Indigenous Knowledge; 5. Kolyma: Major river of the Northeastern Siberia; and 6. Iyengra: Artisanal gold mining and Evenki taiga nomadism. Supplementary data to this article can be found online at doi:https://doi.org/10.1016/j.scitotenv.2022.156566.

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