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Systematic review of documented Indigenous Knowledge of freshwater biodiversity in the circumpolar Arctic

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Abstract

1. Indigenous Peoples in the Arctic have for millennia relied on freshwaters for drinking water and freshwater species that comprise important subsistence harvests, which promotes a strong connection to the land and unique understanding of organisms and ecosystem processes and changes. Despite the importance of freshwater biodiversity and ecosystem services to Arctic Indigenous communities, there have been limited attempts to summarise available Indigenous Knowledge (IK) regarding Arctic freshwater systems and to understand how conservation can benefit from this knowledge base.
2. This paper presents a systematic review of literature documenting circumpolar Arctic IK with a focus on freshwater biodiversity in Canada, Greenland, Fennoscandia (Norway, Sweden, and Finland), Russia, and the U.S.A. (Alaska). Standardised search terms and methodologies were used to locate relevant documents using Google Scholar and Google Advanced search engines. Thematic coding was used to identify freshwater biodiversity themes within the identified documents.
3. Documented IK of freshwater biodiversity was found from all five geographic regions and included data on both species presence and habitat changes with potential to affect biodiversity. Canada had the highest number of relevant documents ($n = 127$), followed by the U.S.A. (Alaska; $n = 116$), Fennoscandia ($n = 38$), Russia ($n = 27$), and Greenland ($n = 5$). The number of relevant documents with IK published per year was highest in most recent years, from 2010 onwards, in all geographic regions.
4. Fish represented the highest number of faunal observations with 59 species observed, approximately half of which were Salmonidae (29 species). Local-scale assessment of fish diversity found observations of the highest number of species (11–25) in Alaska, and individual observations of 6–10 species were found throughout Alaska, mainland areas of Canada, and the Kola Peninsula in Russia. Documented IK also contributed new information on historical fish diversity and indicated local-scale loss or gain of species. Such information is of vital importance to provide long-term records of fish composition and abundance, especially when this information does not exist in other knowledge bases such as western science datasets.

5. Indigenous Knowledge included observations of changes in freshwater and terrestrial habitat associated with a warming climate, such as: decreasing water levels and more draining/drying of lakes and rivers, a shorter period of ice cover (late freeze and early break-up), decreasing ice thickness, and increasing occurrence of permafrost thaw and eroding banks. Such observations by those who actively rely on Arctic freshwater ecosystem services are important because they signify that change is occurring and that action is needed to mitigate the impacts on freshwater habitats and the biodiversity therein.
6. This study demonstrates that previously documented IK provides valuable information towards determining freshwater biodiversity baselines and patterns of change in the circumpolar Arctic. However, these results do not sufficiently cover the depth and breadth of IK on freshwater biodiversity and ecology held by Indigenous communities. Further work incorporating Indigenous worldviews around freshwater ecology would provide context to the knowledge collected and a deeper understanding of Arctic circumpolar freshwater environments.

KEYWORDS

climate change, fish, lake, river, Traditional Knowledge

1 | INTRODUCTION

The importance of conserving and maintaining biodiversity is a fundamental element of a healthy ecosystem and a common tenet of many knowledge systems, such as those of the circumpolar Arctic Indigenous Peoples (Gadgil, Berkes, & Folke, 1993). Although the various knowledge systems include different terms to describe the elements of biodiversity (Posey, 1999), the essential and shared components of the biodiversity concept include and require ecosystem function to be resilient if ecosystem services are to be maintained (CAFF, 2002, 2013; Reid et al., 2005). The concept that all species are connected through food webs and, in turn, are influenced by environmental forces is well-understood by harvest-based Indigenous communities around the globe (Gadgil et al., 1993; Merculieff et al., 2017; Mustonen & Ford, 2013). Despite the importance of freshwater biodiversity and ecosystem services to Arctic Indigenous communities, there have been limited attempts to summarise Indigenous Knowledge (IK) regarding Arctic freshwater systems and understand how monitoring and conservation can benefit from such knowledge.

The importance of freshwater ecosystem services in the circumpolar Arctic is reflected in Indigenous Peoples having relied for millennia on local ecosystems to provide wild fauna and flora for subsistence purposes (Huntington et al., 2013; Mazzocchi, 2006; Merculieff et al., 2017; Michelutti et al., 2013; Mustonen & Ford, 2013). Freshwater ecosystems have provided sustenance for circumpolar Indigenous peoples since time immemorial (Huntington et al., 2013; Merculieff et al., 2017). Lakes and rivers provide drinking water, and a variety of freshwater species comprise important subsistence harvests, including anadromous and non-anadromous fish, waterfowl, mammals, and shoreline plants (CAFF, 2010; Huntington et al., 2013; Merculieff et al., 2017). In the past, peat from edges of ponds was collected to build houses (Merculieff et al., 2017). Athabascan People have used the Yukon River and its tributaries for hunting and fishing, travel, driftwood collection (for firewood), spiritual purposes, drinking, sanitation, recreation, and other domestic uses (Wilson, 2014). Many freshwater fish species, especially salmonids, were used to feed dog sled teams, an important form of transportation in areas of the Arctic, especially from the mid-19th to 20th centuries (Andersen, 1992; Nuttall et al., 2005). Air drying freshwater and marine fish, a technique that allows for the preservation of fish in dry Arctic climates, has remained an important preservation technique for subsistence harvests by Indigenous groups across the circumpolar Arctic (Mustonen & Mustonen, 2016; Spearman, Nageak, & Elders of Anaktuvuk Pass, 2005; Wishart, 2014). Inuit communities harvesting wildlife in freshwater catchments have also contributed nutrient inputs into these systems, thus affecting the freshwater ecosystems where they have lived (Michelutti et al., 2013).

The reliance of Indigenous communities on freshwater ecosystem services promotes a strong connection to the land and unique in-depth understanding of organisms and ecosystem processes (ACIA, 2005; Mazzocchi, 2006; Merculieff et al., 2017; Mustonen & Ford, 2013). For example, knowledge of animal behaviour and phenology supports harvesting and hunting activities (ACIA, 2005; Merculieff et al., 2017). To recognise this unique and rich knowledge base, The Convention on Biological Diversity adopted guidelines that recognise “the close and traditional dependence of many Indigenous

Peoples and local communities on biological resources [and] the contribution that Traditional Knowledge can make to both the conservation and the sustainable use of biological diversity" (Convention on Biological Diversity, 2017). This connection of Indigenous Peoples with the land allows them to observe and develop first-hand knowledge of biodiversity and changes to local ecosystems. Examples of such observations and knowledge include shifts in the timing of ice on/ice off on lakes, changes to snowpack duration, shifts in plant and animal phenology, and changes to wildlife population size, diversity, and animal health (ACIA, 2005; Alexander et al., 2011; Ford & Pearce, 2010; Merculieff et al., 2017). Clearly, Arctic Indigenous Peoples have an intimate experience with, and extensive knowledge of, freshwater ecosystems that could be applied to improve assessments of biodiversity in Arctic freshwaters and the effects of environmental change on these systems.

In addition, the inclusion of IK in Arctic freshwater biodiversity and climate assessments is important to provide a more holistic understanding of observed or studied phenomenon and to include Indigenous voice and local expert knowledge (Alexander et al., 2011; CAFF, 2013; Furgal, Dickson, & Fletcher, 2006; Merculieff et al., 2017; Mistry & Berardi, 2016). Climate change is directly and indirectly affecting Arctic freshwater ecosystem biodiversity through changes to physical and chemical properties, and alterations to species composition and the geographic distribution of species (Culp, Goedkoop, et al., 2012; Ford & Pearce, 2010; Lento et al., 2019; Meltofte, 2013). Moreover, increased rates of development and resource extraction in Arctic regions including hydropower dams, mining, sport and commercial fisheries, and sport hunting all threaten water quality, habitat condition, and the ecosystem services provided by Arctic freshwaters (Culp, Lento, et al., 2012; Huntington et al., 2013; Mustonen & Mustonen, 2016). Learning from Arctic Indigenous Peoples understanding and observations of climate change and development impacts is critical to providing a better understanding of the state of Arctic freshwaters.

Arctic freshwater biodiversity is not well understood and critical gaps exist in our knowledge (Meltofte, 2013), particularly in remote areas of the Arctic that are difficult to access (Lento et al., 2019). Understanding both the historical and current state of freshwater biodiversity in the Arctic will benefit from the use of all possible sources of knowledge in monitoring and management of these ecosystems (CAFF, 2013). The Freshwater Group of the Circumpolar Biodiversity Monitoring Program (CBMP), part of the Conservation of Arctic Flora and Fauna (CAFF) working group of the Arctic Council, has conducted the first circumpolar assessment of the state of Arctic freshwater biodiversity to support monitoring and assessment of changes resulting from climate change and development (Lento et al., 2019). The assessment focused on biodiversity data compiled from western science (WS), a term used here and throughout this paper following the definitions of Cajete (2000) and Mazzocchi (2006), including government, industry, and academic monitoring data from all Arctic countries. A high priority for this assessment was to ensure inclusion of IK, recognising its valuable contribution to characterising and monitoring freshwater biodiversity in the Arctic. However, the CBMP also recognises that it is critical to approach this in a way that is respectful to the knowledge holders and does not seek to ignore their right to ownership of their knowledge. The first step in including IK in this assessment was to understand the scope and breadth of documented IK that might contribute to widespread assessment of biodiversity.

Although previous efforts have focused on summarising IK to describe general impacts of climate change on Arctic ecosystems (e.g. see ACIA, 2005; Ford & Pearce, 2010; Merculieff et al., 2017), this manuscript presents the results of a systematic literature review using thematic coding to summarise previously documented observations from circumpolar IK on Arctic freshwater biodiversity (defined here as the variety of organisms found in Arctic freshwater ecosystems) in Canada, Greenland, Fennoscandia (Norway, Sweden, and Finland), Russia, and the U.S.A. (Alaska). This is the first time this approach has been applied to this specific topic. The specific goals of this systematic literature review were to: (1) improve understanding of documented IK resources on the topic of Arctic freshwater biodiversity; (2) determine if observations from previously documented IK could contribute to mapping freshwater biodiversity across the circumpolar Arctic; (3) determine if observations from previously documented IK could support the identification of emerging trends in Arctic freshwater biodiversity and habitats; and (4) identify synergies or discrepancies between IK and WS knowledge bases, or new information or trends in Arctic freshwater biodiversity not documented through WS methods. In this review, we did not attempt to analyse or interpret the previously documented IK itself, or to contrast regional differences in how IK was collected or documented. Instead, the aim was to show what observations on Arctic freshwaters have been recorded in the literature from IK, and to understand how previously documented IK can be included in biodiversity assessments.

This manuscript presents the results of the emergent themes in Arctic freshwater biodiversity, as identified through IK in published literature. Despite not all of the retrieved documents having studies focused specifically on IK of Arctic freshwater biodiversity, considerable amounts of information about Arctic freshwater biodiversity and habitats were present allowing for a preliminary understanding of these systems. The emergent themes primarily provided knowledge on diversity and abundance of freshwater organisms including fish, birds, mammals, and plants as well as the state of, or changes to, freshwater habitats. The results present an initial inventory and state of recorded Indigenous Knowledge of Arctic freshwater taxa and ecosystems for each country. Ultimately, suggestions are made for improvements to the incorporation of IK into future Arctic freshwater biodiversity assessments.

2 | METHODS

A systematic literature review of previously documented IK on freshwater was conducted following the methods of Kouril, Furgal, and Whillans (2015) and Breton-Honeyman, Furgal, and Hammill (2016). Google Scholar™ and Google™ Advanced Search were used

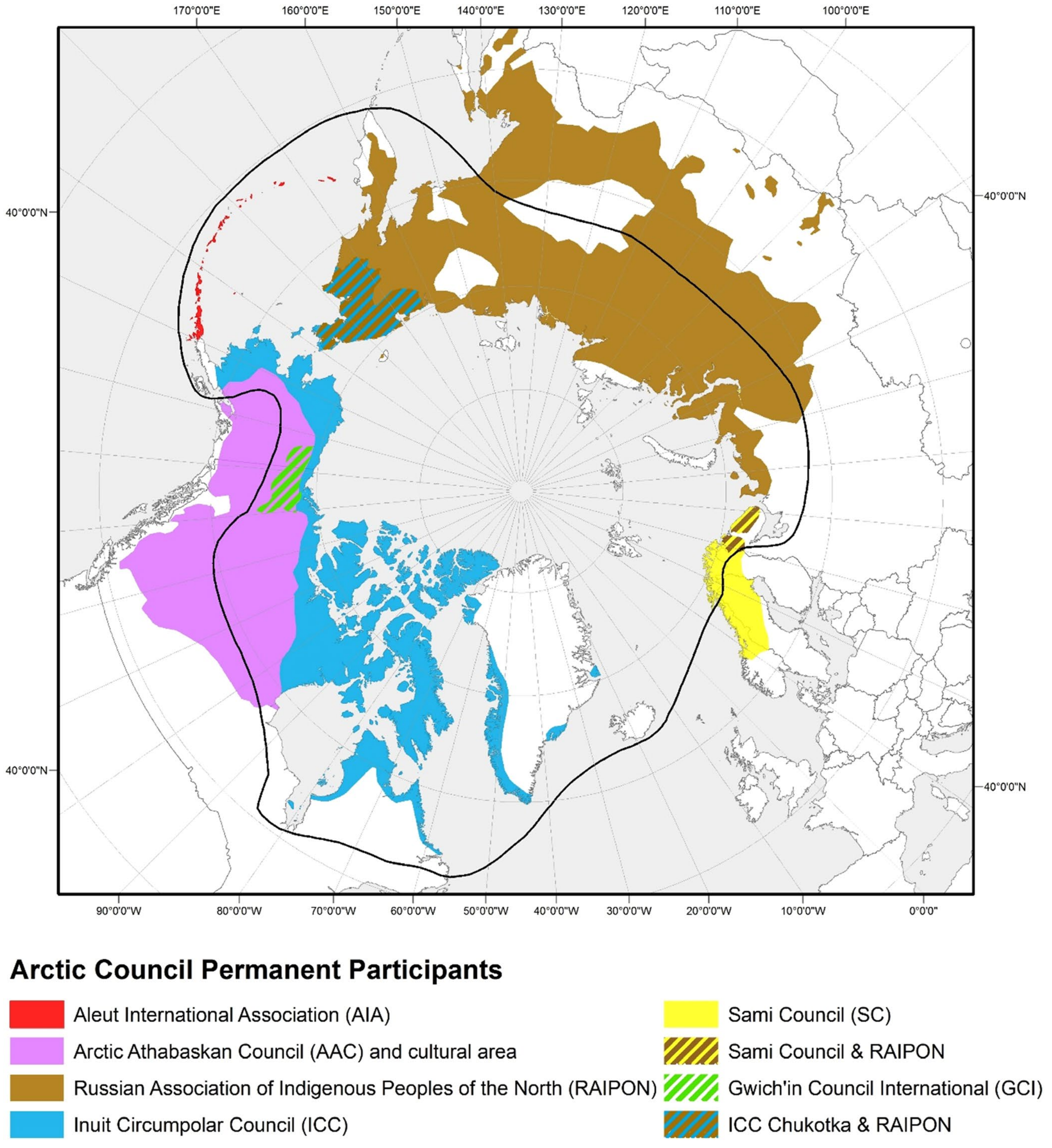


FIGURE 1 Arctic Council Permanent Participants regions in the circumpolar Arctic (solid colours) and areas of overlapping jurisdictions (hashed regions). The systematic literature review of Indigenous Knowledge on freshwater biodiversity was conducted in the coloured and hashed areas within the Arctic Biodiversity Assessment Arctic boundary (solid black line). Source for Arctic boundary and Permanent Participant layers: Conservation of Arctic Flora and Fauna (caff.is).

to search for peer-reviewed and grey literature. The two Google™ search engines were chosen as they are open source, multi-national, allow advanced search functions, and provide results for a wide variety of formats of documented knowledge including peer-reviewed journal articles, non-peer-reviewed papers and reports, conference and workshop proceedings, documentaries and videos, and other knowledge sharing formats. Additionally, using Google™ search engines provided a standardised approach to searching for documents across the circumpolar region. Though other databases are available that are specific to each country, Google™ search engines were chosen to standardise our approach across all study regions. Sources included in the review required authorship. Websites, periodicals, newspapers, magazines, and raw data were not considered due to the difficulty in assigning authorship to the documented knowledge.

Searches were focused within the Arctic boundaries as defined by the Arctic Biodiversity Assessment (Meltofte, 2013; Figure 1). This boundary was used to ensure the limits of what was considered Arctic were clearly defined, and to ensure consistency with the CAFF-CBMP circumpolar assessment of Arctic freshwater biodiversity, of which this study is a part (see Lento et al., 2019). Only knowledge from Indigenous Nations within the CAFF Permanent Participants (http://www.arctic-council.org/index.php/en/about-us/permanent-participants) was included in the search (Figure 1). Searches were conducted for each country or region within this boundary (i.e. Canada, Fennoscandia [Finland, Norway, Sweden], Greenland [Kingdom of Denmark], Russia, and U.S.A. [Alaska]). For each region, the appropriate Google^{TM} extension was used (i.e. .ca for Canada; .dk for Greenland for Google Scholar^{TM} search and .gl for the Google^{TM} Advanced Search, as the latter was not available for Google Scholar^{TM} ; .fi for Finland; .no for Norway; .se for Sweden; .ru for Russia; .com for Alaska), to ensure documents from each specific region would be captured. Based on preliminary search results, combinations of eight terms were used to conduct the searches: name of country or region (Russia, Alaska, etc.), name of cultural group (Nenets, Aleuts, etc.), "knowledge", "freshwater", "fresh AND water", and "lake OR river". Due to the high number of hits resulting from Google searches, the first 200 results were assessed for relevance based on title, description, or abstract (where available).

Potentially relevant documents were downloaded and a review of the full text or video file was used to determine inclusion of IK on freshwater biodiversity. Initial searches were completed by the research team in December 2018; inter-searcher tests were conducted for two regions to ensure consistency in the search efforts, resulting in a complete set of documents to analyse by January 2019. Searches sometimes produced the same documents and repeats were culled. Focus was solely on IK. Local knowledge (e.g. information from non-Indigenous fishers) was not included, although sometimes documents used the term *local knowledge* to refer to phenomena observed by *local* Indigenous communities. IK in any retrieved document was considered to be collected by appropriate means with full, prior, and informed consent of the knowledge holder. As there was no way to confirm this, it had to be assumed this was accurate and truthful on the part of the author of the document. In some cases, documents clearly identified information contained within was IK; in other cases, documents contained results of harvest data or interviews with hunters that contained content with relevance to IK without explicitly stating inclusion. Subsistence harvesting, which is important for Indigenous communities both in terms of food security and cultural identities, is intrinsically tied with IK. Subsistence harvest depends on knowledge of the land, animal behaviours, and ecosystems in order to be successful (e.g. Huntington et al., 2013). Additionally, subsistence harvest studies offer great potential to contribute IK towards assessments of Arctic freshwater biodiversity through descriptions of species' geographic ranges, abundance, and diversity of encountered species. As such, and as the purpose of this study was to query the status of previously documented IK on Arctic freshwater biodiversity using a systematic review process, harvest study documents were included in the review.

A thematic content analysis (Cope, 2010; Saldaña, 2015) of all relevant sources was used to identify emergent themes in documented IK on the topic of freshwater biodiversity. This led to the creation of a codebook (coding structure [Table S1] and set of rules for coding) based on emergent themes (Cope, 2010; Saldaña, 2015). Additionally, inter-coder variability (also known as inter-rater reliability) tests were performed using a sample of four relevant papers from two regions to increase the reliability of coding . Tests were conducted by comparing coding results between the two coders, along with two additional trained qualitative coders not involved in the coding (Armstrong, Gosling, Weinman, & Marteau, 1997; Lombard, Snyder-Duch, & Bracken, 2002). In general, scores over 75% compatibility between coders are understood as rigorous in projects involving more than one coder (Armstrong et al., 1997; Lombard et al., 2002). For this research, compatibility between coders was set to at least 85% to ensure rigour in coding. All four test coders used the codebook to code the four test documents. Results of each document were compared between coder's results. In instances where differences between coding occurred, coders discussed the results and refined the rules for coding to ensure consistency. The codebook and coding were then revised until at least 85% compatibility was obtained. The codebook was then updated based on outcomes of inter-variability tests.

Developing the final codebook was iterative and involved a process of collapsing some categories to ensure rigour in the coding process. All relevant documents were then coded using the codebook. Only documents written in English or Russian were reviewed due to fluency of the coders. Sections of books available online were coded when the book could not be obtained. Summary plots were created to compare the number of hits in the literature searches for each region and the number of relevant documents for each geographic region (from all searches, as documents were often relevant to multiple regions). The number of relevant documents published per year was also plotted by geographic region to assess shifts in document availability over time. Microsoft® Excel was used for coding analysis.

All organisms that live in freshwater were included in the thematic coding even if the freshwater environment is only used for part of a species' life cycle. Freshwater was considered to include lakes, rivers, streams, creeks, ponds, wetlands, marshes, fens, and bogs. Estuaries were considered part of the freshwater environment as IK did not distinguish these two environments as separate. To synthesise thematic content analysis (coding) results, tallies of the number of times each code appeared in the literature were completed for each country or region to show patterns among themes and between regions. Resulting data from the coding exercise were examined for species presence as well as emergent trends or indicators of biodiversity, if any. In addition, maps of the resulting thematic coding data were created by determining coordinates of locations described in the literature. Each coded item was assigned coordinates by taking the described location (e.g. river, lake, specific place, community) associated with each observation and cross referencing

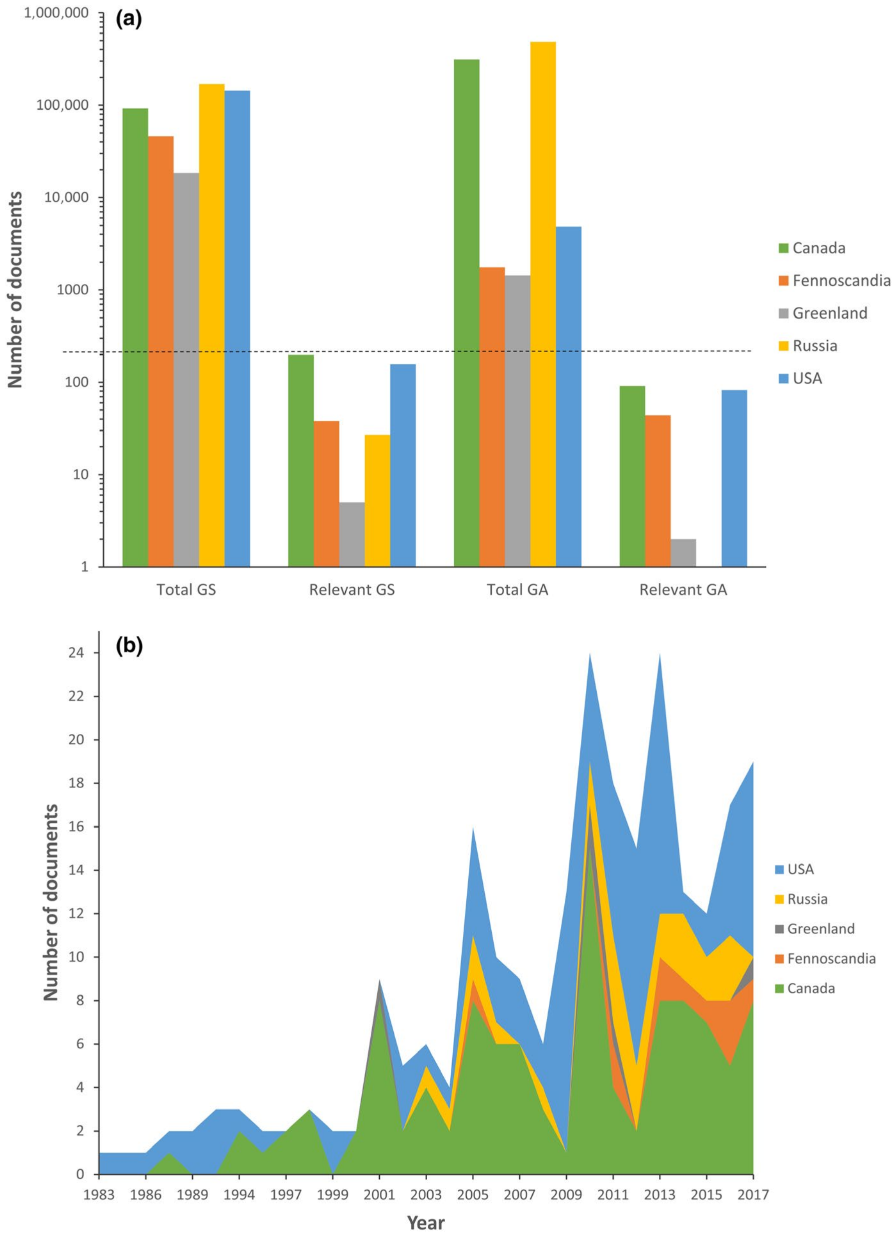


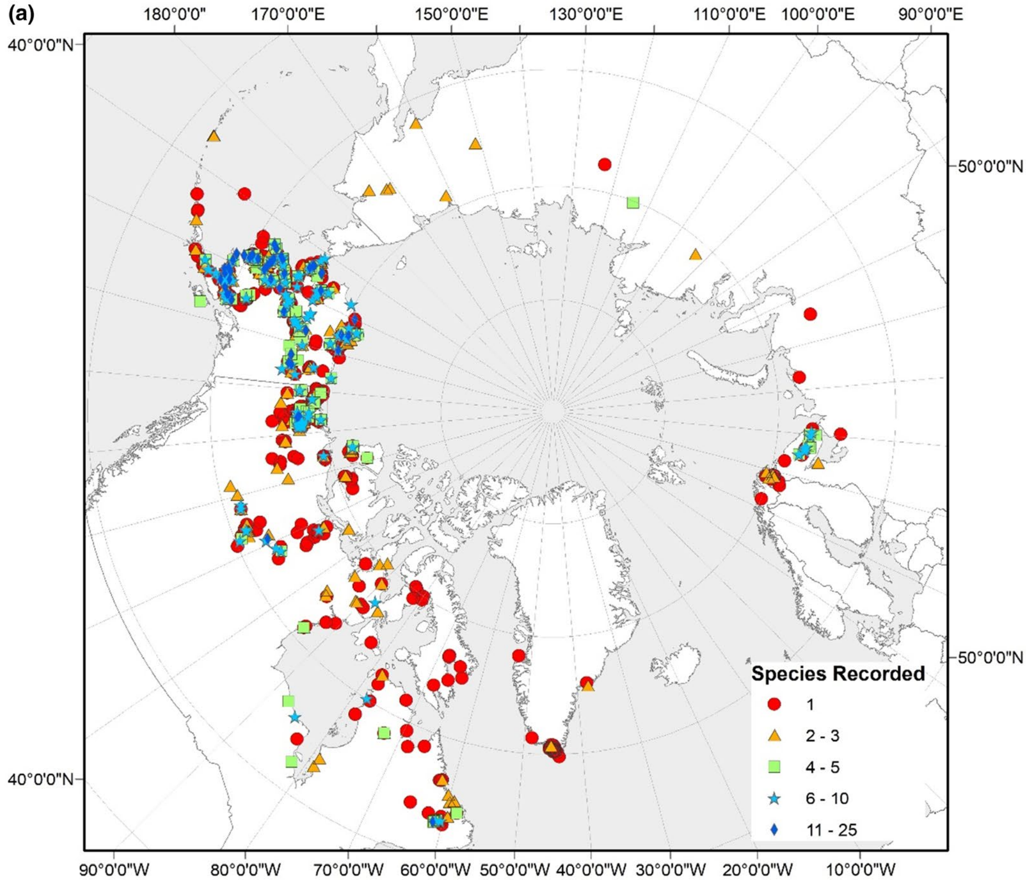
FIGURE 2 (a) Bar graph showing the total and relevant hits in Google Scholar™ (GS) and Google™ advanced (GA) search results per geographic region, with numbers plotted on a logarithmic scale and a dashed line to represent the 200 document cut-off point for relevant hits. Relevant hits include documents from any regional search that were relevant to the indicated geographic region. (b) Stacked histogram of the number of relevant documents published each year from 1983 to 2017, grouped by the geographic regions for which the documents were searched

maps or descriptions with Google Maps to obtain the most accurate point possible. Coordinates and associated thematic coding results were entered into Microsoft Excel tables and maps of results were created in ArcMap Version 10.3 (ESRI, St. Paul, Minnesota, U.S.A.).

3 | RESULTS

Documented IK of freshwater biodiversity was found from all five search regions (Canada, Fennoscandia, Greenland, Russia, and the U.S.A. [Alaska]) and included data on both species presence and habitat changes with potential to affect biodiversity. IK was retrieved from peer-reviewed literature (n = 82) and grey literature that included reports (n = 124), books (n = 19), book sections (n = 17), videos (n = 9), theses (n = 32) and conference proceedings (n = 2). A total of 285 documents were coded. Some documents included IK from more than one country or region and some search terms identified documents from outside the searched region, but still within the defined search area (Figure 1). The total number of hits in the Google Scholar™ search was similar among geographic regions, whereas there were far more hits for the Google™ advanced search in Russia and Canada than in other regions (Figure 2a). When only the first 200 hits were considered for relevance, knowledge on freshwater biodiversity was described in the highest number of documents in Canada (n = 127), followed by the U.S.A. (Alaska; n = 116), Fennoscandia (n = 38), Russia (n = 27), and Greenland (n = 5; Table S2; Figure 2a). In part, the larger number of relevant documents in Canada and the U.S.A. appeared to be a reflection of the longer period over which documents were published, as documents from these two countries dated back to the early-mid 1980s, whereas relevant IK documents from Greenland, Fennoscandia, and Russia were dated 2001 or later (Figure 2b). The number of relevant documents published per year

(a)



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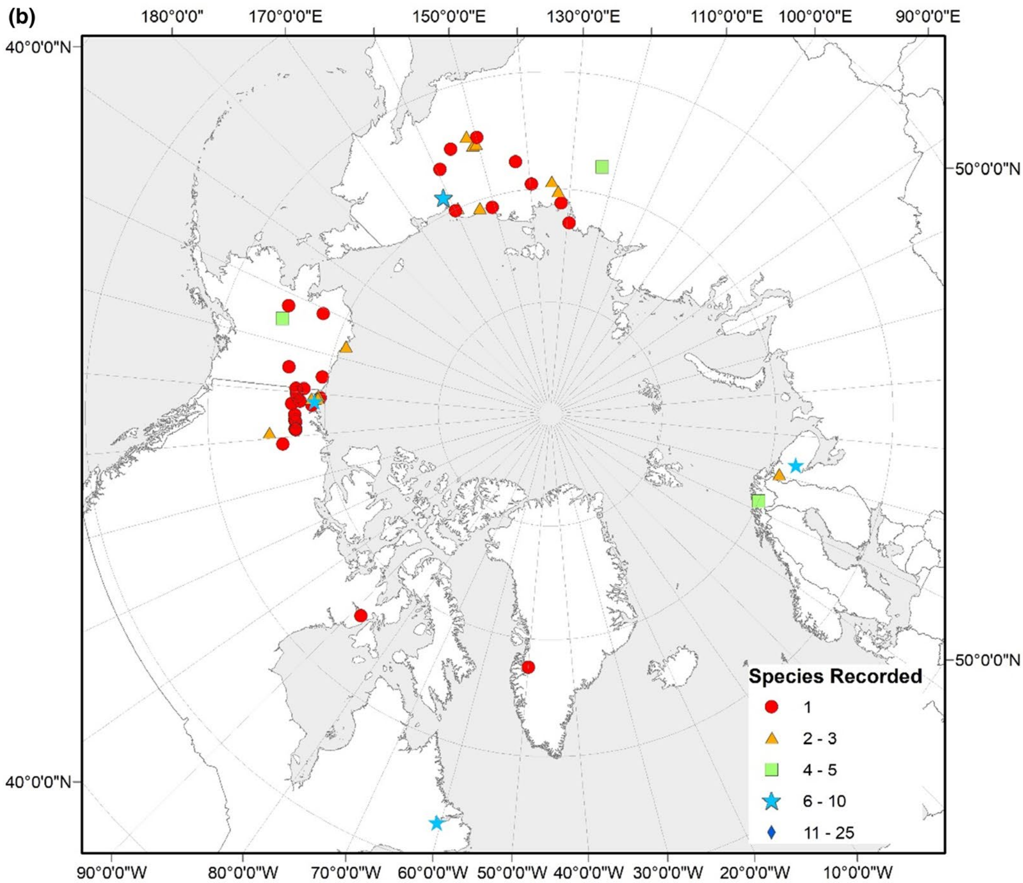

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FIGURE 3 Map of freshwater fish biodiversity for the (a) contemporary (1950-present) and (b) historical (1800–1949) time periods, based on documented Indigenous Knowledge from the circumpolar Arctic. Tallies of the number of fish species from both *Freshwater Fish Species* and *Locally-Named Freshwater Fish* codes were calculated to categorise number of freshwater fish at each site described in the reviewed literature

increased in all countries after 2000, and there were several peaks from 2010 to 2017 across all geographic regions (Figure 2b).

Thematic coding revealed seven overarching emergent themes: *Freshwater Fish Species Presence*; *Locally-Named Freshwater Fish*; *Other Organisms*; *Number of Fish Species at a Site*; *Changes in Fish Species Abundance*; *Changes to Freshwater Habitat*; and *Time Period Species Observed* (Table S1). These categories emerged due to the scope of the systematic literature review—the relevance of IK to understanding Arctic freshwater biodiversity—rather than as a reflection of how Indigenous Peoples themselves might think about their knowledge of freshwater species.

Fish represented the greatest number of species observations with a total of 59 species identified (Table S1). The family Salmonidae represented nearly half the total number of species with 29 distinct species identified. Additionally, 23 *Locally-Named Freshwater Fish* were observed (Table S1). This code was used when the species of fish observed was not explicitly stated. The number of identified fish species varied greatly among the search regions with Canada having the highest number of fish biodiversity at 36 species, followed by Alaska at 32 species, Russia at 28 species, Fennoscandia at six, and Greenland with the lowest number at two fish species. Tallies of the number of fish species from both *Freshwater Fish Species* and *Locally-Named Freshwater Fish* codes were used to categorise the number of freshwater fish species at each site (Table S1) and to create a map of fish biodiversity based on documented IK for the circumpolar Arctic (Figure 3). Local-scale patterns in fish diversity, based on individual observation locations, indicated that observations of the greatest number of species (11–25) were concentrated in Alaska, and observations of 6–10 species were found throughout Alaska, mainland areas of Canada, and the Kola Peninsula in Russia (Figure 3a). Historical (1800–1949) observation data of fish species were part of the coding results, including observations of 2–10 species in Fennoscandia, eastern Russia, Alaska, and western Canada (Figure 3b).

Changes in Fish Species Abundance was another emergent theme. Noted changes to fish species abundance included shifts in numerical abundance (increase or decline) as well as changes in abundance that reflected compositional changes, such as the disappearance of species or appearance of new species, with Alaska and Canada seeing the most changes in all four of these categories (Table S1). Increased abundance of freshwater fish was the predominant observation across much of the Arctic, although observed shifts in numerical abundance at higher latitudes in Canada included many observations of decreasing fish abundance (Figure 4a). The most common observation of compositional change was that of new fish species, which was noted across the Arctic (Figure 4b). There were notably a similar number of observations of fish species loss and gain in Fennoscandia (Figure 4b).

The *Other Organisms* thematic code included IK on freshwater biodiversity of birds, mammals, reptiles, invertebrates, and flora with 112 distinct organisms observed (Table S1). Birds and waterfowl were the second most identified organisms after fish with 37 distinct species identified from IK in the coded literature. A total of 51 bird taxa were identified (species level plus coarser taxonomic resolution), followed by mammals (27 taxa), invertebrates (21 taxa), plants (11 taxa), and amphibians (two taxa).

The thematic code *Changes in Freshwater Habitat* included observations of changes to the freshwater environment that had the potential to impact freshwater biodiversity. Documented IK of transformations to freshwater habitat spanned observations of changes to: water quality including changes to salinity and algae density, freshwater ice regimes, water temperature, water levels in lakes and rivers, aquatic vegetation, hydrological cycle, and impacts from species alterations in the freshwater environment, with declining water levels and thawing permafrost being the most commonly discussed changes to Arctic freshwaters (Table S1). Canada had the most documented IK of changes to the freshwater environment, followed closely by Alaska and Russia. Greenland and Fennoscandia had fewer examples of documented IK of changes in freshwater (Table S1).

Documented habitat changes were mapped to present localised IK of changes to the freshwater environment for the circumpolar Arctic. Hydrological changes were mapped in Figure 5, including widespread observation of draining and drying lakes and rivers across the Arctic (Figure 5a), as well as decreased water level, which was particularly common in observations across Canada (Figure 5b). In Alaska, there were a number of observations of decreased water level combined with increased sand bars (Figure 5b). Changes in ice timing included observations of late freeze-up, early break-up, or a combination of the two across much of the Arctic (Figure 6a), whereas observations of ice thickness predominantly noted decreases in thickness (Figure 6b). Water quality was noted to be changing (predominantly in Alaska) or declining across much of the Arctic (Figure 7a). Finally, there were also observations of terrestrial habitat changes that could have implications for freshwater quality and habitat condition. Notably, there were many observations of permafrost thaw and/or eroding banks in Alaska, western Canada, and eastern Russia, whereas lower latitudes of North America and Fennoscandia had observations of increased vegetation (Figure 7b).

4 | DISCUSSION

4.1 | Documented IK on Arctic freshwater biodiversity

Despite IK being kept alive through oral traditions for millennia, recent years have seen the rise of documentation of this knowledge

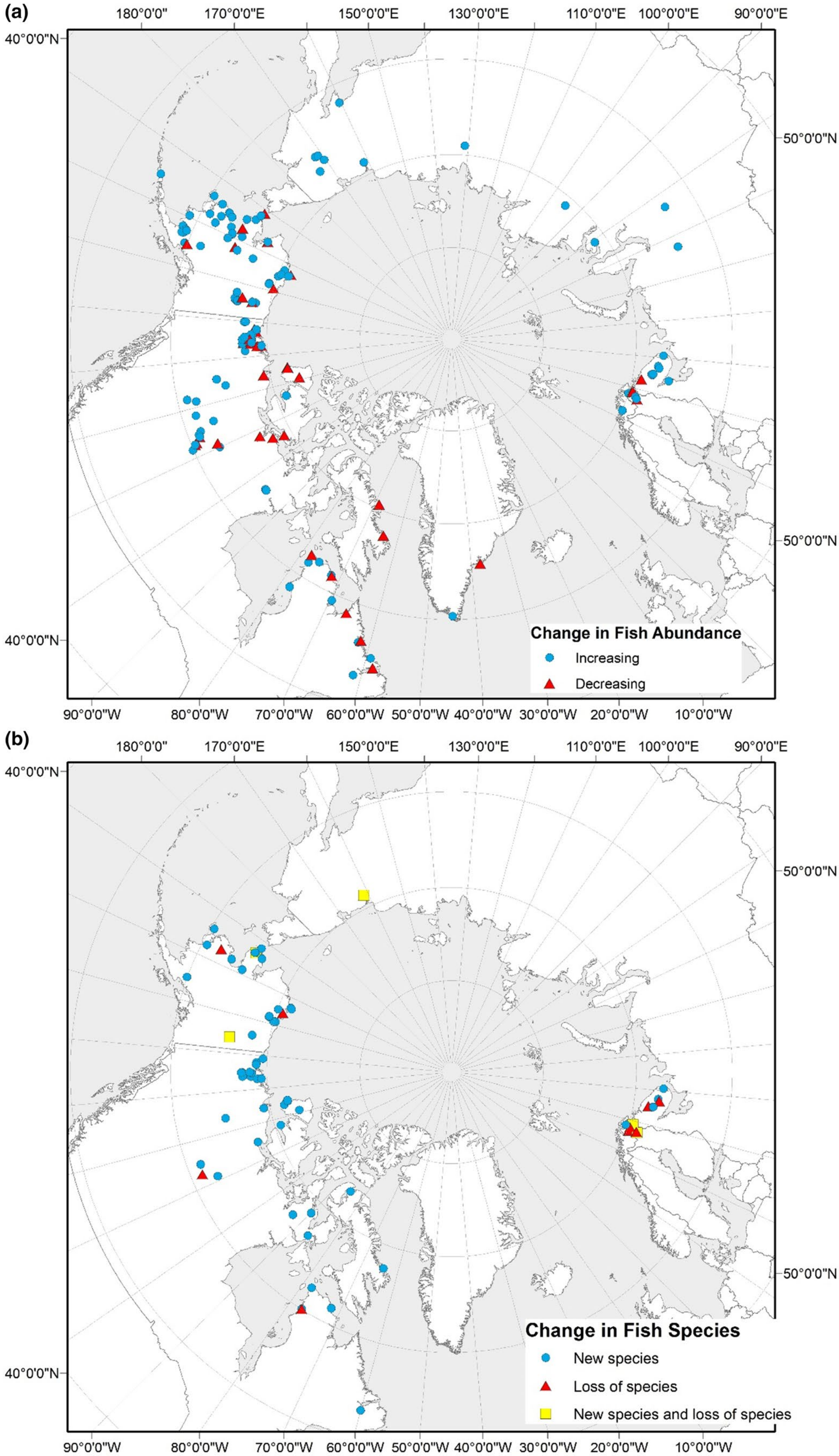

FIGURE 4 Map of observations of changes in freshwater fish (a) abundance (decreasing or increasing), and (b) composition, including new species and loss of species, based on documented Indigenous knowledge from the circumpolar Arctic

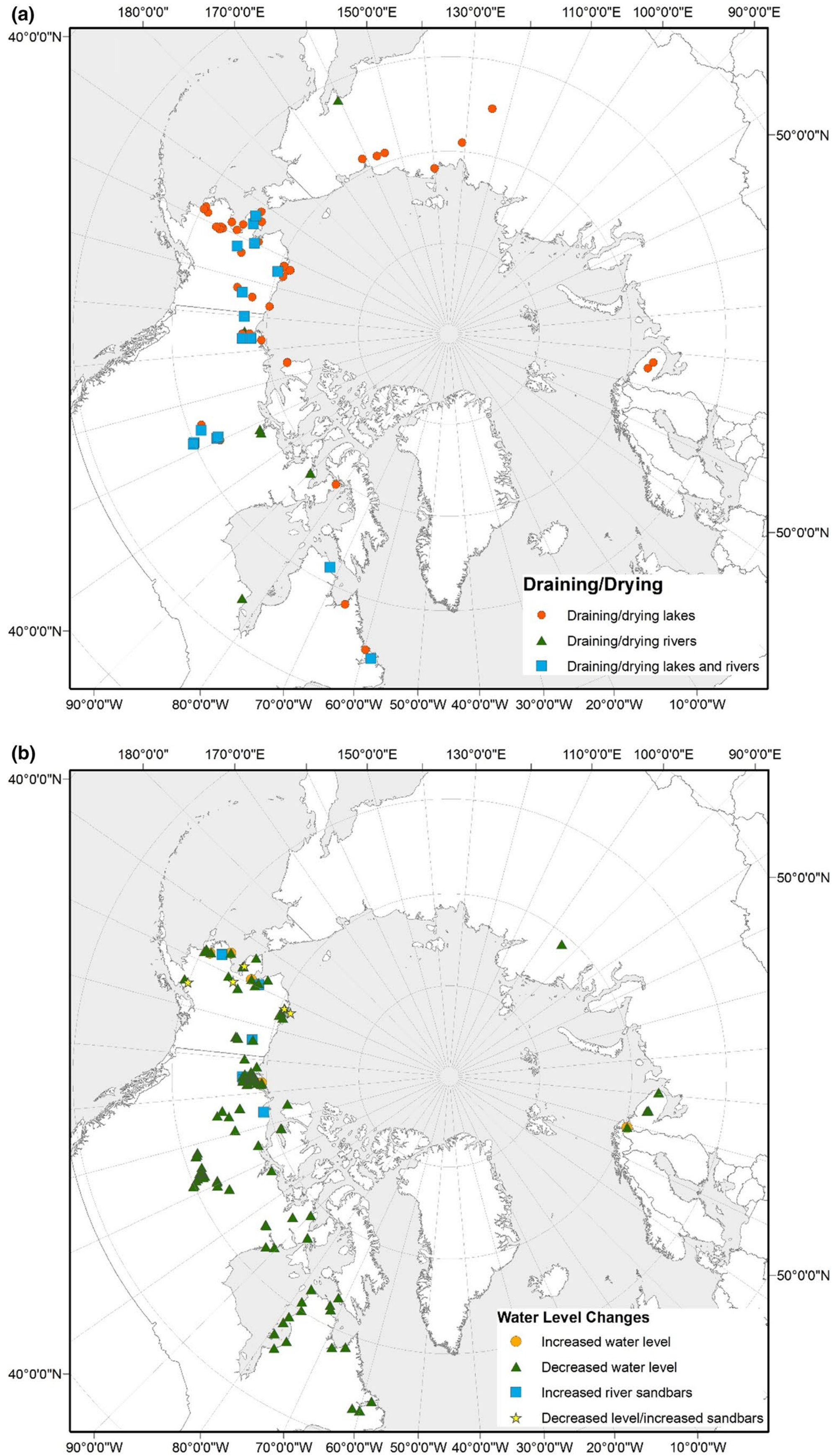

FIGURE 5 Map of freshwater habitat changes based on documented Indigenous Knowledge from the circumpolar Arctic, including (a) observations of draining and/or drying lakes or rivers, and (b) observed changes to water levels

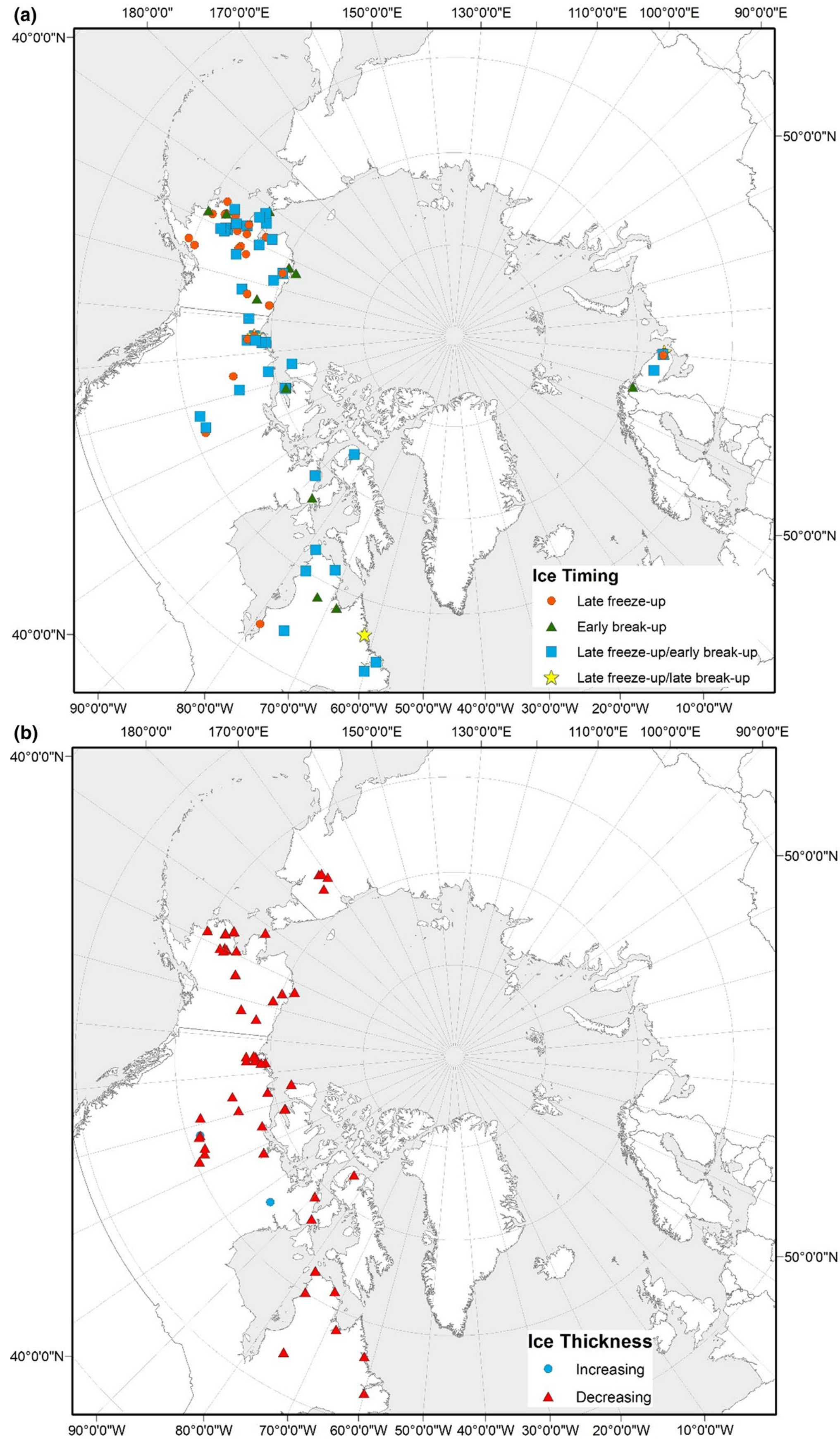

FIGURE 6 Map of freshwater habitat changes based on documented Indigenous Knowledge from the circumpolar Arctic, including (a) observed changes to the timing of ice on and ice off, and (b) observed changes to ice thickness

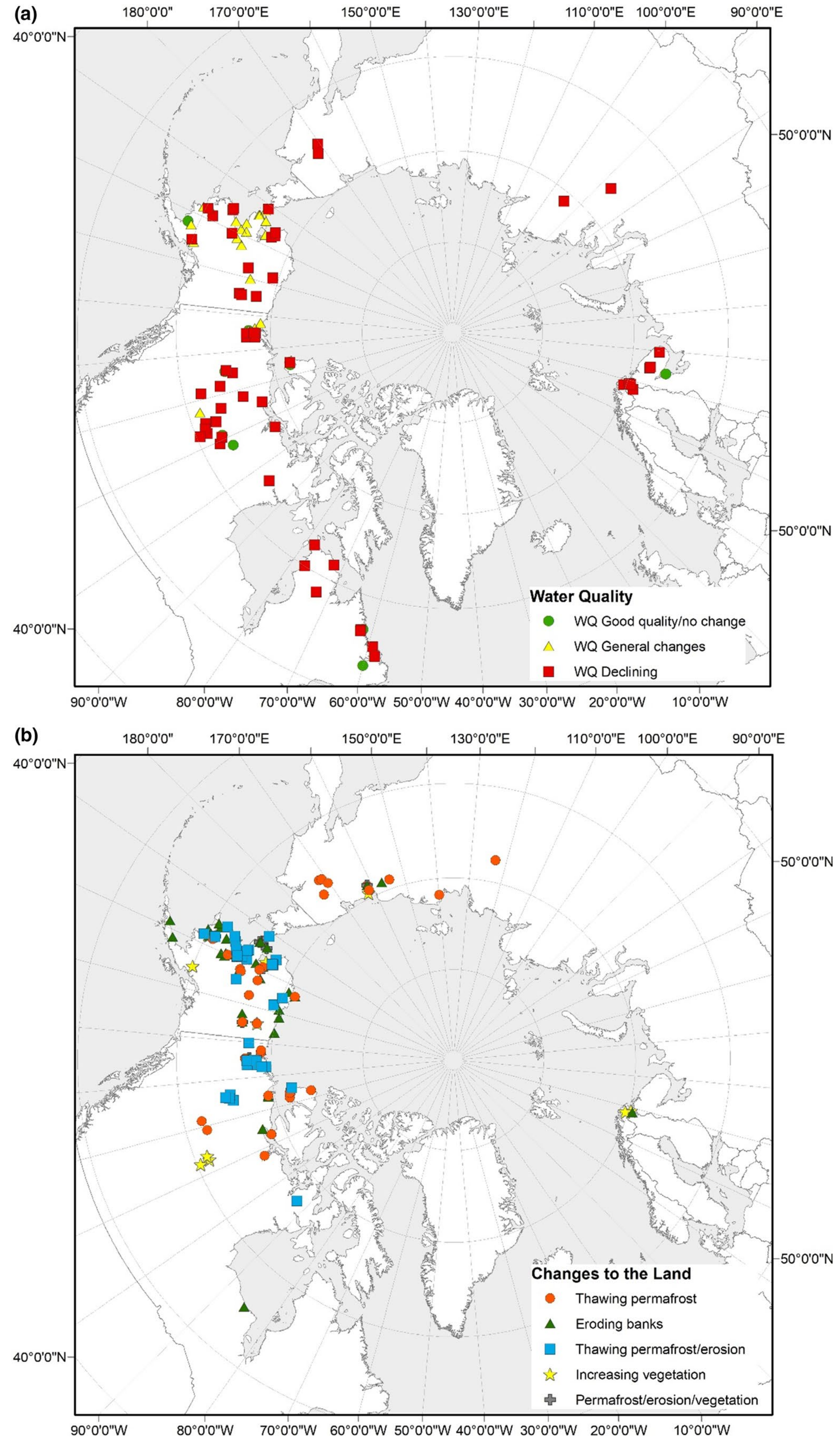

FIGURE 7 Map of freshwater habitat changes based on documented Indigenous Knowledge from the circumpolar Arctic, including (a) observed changes to water quality, and (b) observed changes to shorelines and land, such as thawing permafrost, eroding banks, and increasing vegetation

base by Indigenous Peoples and scholars alike (Huntington et al., 2013; Pulsifer, Laidler, Taylor, & Hayes, 2011). The shift towards the documentation of this knowledge base is reflected in the 285 documents found containing IK on Arctic freshwater biodiversity and habitat, and the increasing number of relevant IK documents in all regions that have been published since the early 2000s.

Thematic coding identified seven overarching themes including species presence (fish species, locally-named fish species, and other organisms), number of fish species at a site, changes in fish species abundance, changes to freshwater habitat with potential to affect biodiversity, and time period in which species were observed. A total of 194 taxonomic groups associated with the freshwater environment were documented through IK (59 fish species plus 23 locally-named fish, 51 bird and waterfowl taxa, 27 mammals, 21 invertebrates, 11 plants, and two amphibians) across all five search regions (Canada, Greenland, Fennoscandia, Russia, U.S.A. [Alaska]), demonstrating a wealth of information on Arctic freshwater biodiversity contained within the body of documented IK.

4.2 | New biodiversity information from IK and synergies with WS knowledge

Fish were the most recorded species within the documented IK, followed closely by birds and waterfowl. These species observations improved the accuracy of existing species distribution maps and estimates of regional taxonomic richness for these groups. For example, there are 100 fish species known to occur within the Arctic region as defined by the CAFF boundary, but the CBMP assessment of circumpolar fish monitoring and research data (largest compilation of WS knowledge on Arctic freshwater fish assemblages) included observations of only 56 species (Laske et al., 2022). Combining observations of fish presence from IK with those from WS datasets improved our knowledge of species distributions. For example, 17 freshwater or anadromous fish species were recorded from IK that were not found in the circumpolar fish monitoring data collected by the CBMP (Laske et al., 2022), including *Acipenser ruthenus*, *Acipenser sturio*, *Brachymystax lenox*, *Carassius carassius*, *Chrosomus eos*, *Clupea pallasii*, *Coregonus migratorius*, *Coregonus muksun*, *Cottus aleuticus*, *Cottus ricei*, *Microgadus proximus*, *Perca flavescens*, *Percopsis omiscomaycus*, *Platygobio gracilis*, *Rhinichthys cataractae*, *Stenodus nelma*, and *Thaleichthys pacificus*. In part, the addition of new species records was due to increased spatial coverage of IK relative to monitoring data, including additional regions in Russia and southern Alaska, and increased spatial coverage across Canada. Notably, documented IK included observations of several fish species primarily or solely found in Siberia (including *Coregonus muksun* and *Brachymystax lenok*), as well as a record of a critically endangered species (*Acipenser sturio*, the European sea sturgeon), none of which were found in the CBMP assessment of monitoring data (Laske et al., 2022).

Documented IK revealed trends in fish species biodiversity including species disappearances and new species records, information that is often difficult to capture through scientific monitoring methodologies, particularly at such a large spatial scale. Documented IK also included historical records of freshwater fish species observations in North America and Russia that could be compared with modern records to identify other areas where species composition has changed. Such information is of vital importance to provide long-term records of fish composition and abundance, especially when this information does not exist in other forms of knowledge such as WS datasets (Laske et al., 2022; Lento et al., 2019). In particular, information from IK about new species occurrences can help with monitoring the northward movement of eurythermic species that is predicted to occur with continued warming of the Arctic (CAFF & PAME, 2017; Lento et al., 2019). The Arctic Invasive Alien Species Strategy and Action Plan (CAFF & PAME, 2017) lists as one of its key management goals the early detection of invasive species, and notes the importance of using IK as a basis for risk analyses because of the breadth of knowledge related to species presence and occurrence. Thus, documented IK contributed data to complement and bolster sparse WS studies on temporal trends and changes to Arctic freshwater biodiversity.

4.3 | Trends in Arctic freshwater ecosystems from IK

In addition to species presence and trends in biodiversity, knowledge of trends of recent and unprecedented changes to freshwater habitat were documented through IK including changes to freshwater quality, water levels and temperatures, ice regimes, increasing frequency of beaver dams, increasing shoreline erosion, permafrost thaw, and vegetation cover. All of these changes in Arctic freshwater environments have the potential to affect biodiversity (Lento et al., 2019). Notably, the dominant patterns suggested decreasing water levels and more draining/drying of lakes and rivers, a shorter period of ice cover (late freeze and early break-up), decreasing ice thickness, and increased occurrence of permafrost thaw and eroding banks, which are all changes that WS methods have found to be associated with a warming climate (e.g. see examples from WS in Kokelj et al., 2015; Prowse, Wrona, Reist, Gibson, et al., 2006; Prowse, Wrona, Reist, Hobbie, et al., 2006). In particular, observations of permafrost thaw from the IK literature search were consistent with WS studies of the frequency of occurrence of these disturbances across the circumpolar Arctic, which is greatest in the western Canadian Arctic, Alaska, and Siberia (Kokelj et al., 2015). This demonstrates that observations by those who actively rely on Arctic freshwater ecosystem services are crucial and indicate change is occurring and action is needed to mitigate the impacts on freshwater habitats and the biodiversity therein (Bennett & Lantz, 2014; Merculieff et al., 2017; Wyllie de Echeverria & Thornton, 2019). These observations can play a role in identifying key locations in Arctic freshwater systems requiring increased management actions and research (Bennett & Lantz, 2014; Wyllie de Echeverria & Thornton, 2019).

4.4 | Spatial and temporal coverage of Arctic freshwater IK

The results of the thematic coding analysis provided information about current patterns and temporal changes in biotic and abiotic ecosystem components from locations across the circumpolar region, with a particularly high number of records in Canada and Alaska. These results add value to Arctic climate change assessments because they represent the documentation of impacts in remote areas of the Arctic that might not easily be studied through WS studies. For example, IK related to freshwater and anadromous fish species presence and taxonomic richness covered a much greater spatial range in Alaska and Russia (including many locations in the Kola Peninsula and eastern Russia) than WS fish monitoring and research data identified through the CAFF–CBMP circumpolar diversity assessment (Laske et al., 2022). Spatial coverage of documented IK on fish was also greater in Canada than the spatial coverage of available WS fish monitoring data, much of which was focused on fisheries catch statistics for a limited number of common and/or commercially important species (Laske et al., 2022; Lento et al., 2019). Furthermore, IK describing changes in fish abundance and fish species presence was found across the entire circumpolar region, whereas long-term records of fish abundance from WS were only available for select areas. Thus, IK provided valuable information about temporal community dynamics across the entire expanse of the circumpolar Arctic.

It should be noted that the systematic methodology used for identifying and procuring these documents did not yield all relevant IK documents. Region-specific focused literature searches might have been more successful at filling spatial gaps in IK coverage, for example in Russia, where some documents may be less widely available. However, while the systematic literature search was not exhaustive, it was designed to provide a standardised baseline summary of existing documents from across the circumpolar region. We envision that future efforts could build upon these results through regionally intensive literature searches in all local and Indigenous languages, using local search engines. Additionally, unattainable documents could have been procured through requests to researchers and natural resource agencies involved with various projects documenting IK (File S1). Such a procedure, however, would not be systematic and thus not replicable, although future regionally intensive reviews could benefit from such efforts. Also of note, this paper offers results of what can be assessed via the systematic procedure, and thus any absences in this literature review speaks to the ways that IK is being documented, rather than implying that Indigenous Peoples have no knowledge in certain places or for certain topics. For example, some issues such as extraction of oil/gas and other resources, fish stocking, reindeer herding, and other concerns related to development and human activities may be of great concern to Indigenous Peoples in the Arctic. While these topics were not the focus of the documents found in the search, it does not suggest a lack of importance of these topics in relation to freshwater biodiversity.

4.5 | Challenges and approaches for incorporating IK in future biodiversity assessments

Although this systematic review successfully identified relevant documented IK as well as information on emerging themes related to Arctic freshwater biodiversity, there remains a further need for incorporating biodiversity measures from IK in a way that is appropriate and respectful to knowledge holders. For example, despite the data obtained from the systematic literature review of documented IK, the results do not sufficiently cover the depth and breadth of IK on freshwater biodiversity and ecology held by knowledge holders (Ford & Pearce, 2010; Huntington et al., 2013). Arctic Indigenous Peoples have a different worldview of the natural world than what is seen in the WS paradigm, creating an awkwardness in cataloguing IK within existing scientific frameworks (Alexander et al., 2011; Cajete, 2000; Mistry & Berardi, 2016). This is well-described by Wilson (2014; p. 5) who states, "From a Western perspective, water is often treated as an abiotic, or nonliving, element of the physical world. In contrast, the people of Ruby [Alaska] emphasise valuing or respecting the Yukon River and its tributaries as a living, or animate, entity. In this sense, the Yukon River is not merely valued instrumentally, or for its importance as a means of obtaining the minimum ends of human life. Instead, the people of Ruby's complex connectivity to water is indicated through their relationship to the Yukon River, which is of deep sociocultural significance, and in particular, through the view that they are engaged in reciprocal relations of respect with the river." Moreover, the majority of the documents reviewed did not have a research focus on biodiversity, suggesting that considerably more information on biodiversity could be obtained if it was the focus of the research or documentation of IK was specifically focused on this topic.

Those conducting future studies should consider the study purpose and design used to collect IK of Arctic freshwater biodiversity. Many of the reviewed documents relied upon interviews and fieldwork explicitly attempting to document contemporary IK, or studies were funded to ascertain *baseline* conditions or assess impacts in the face of development initiatives. Moving forward, studies involving IK of Arctic freshwater biodiversity should include rigorous qualitative interviews with knowledge holders and diverse methods of engaging with IK such as historical research using archival and oral history, and linguistic methods since Indigenous place names can indicate former ecological conditions (Alexander et al., 2011; Merculieff et al., 2017). Furthermore, it needs to be recognised in future studies that documenting IK may not always be conducive to understanding the question of Arctic biodiversity because Indigenous communities use their knowledge for other endeavors (Merculieff et al., 2017). For example, the retrieved and coded documented IK often focused on understandings of freshwater ecosystems within the lens of practices of ecological management, sustainable harvesting and wildlife health. In addition, not all species are observed or studied by Indigenous Peoples. Fish and waterfowl (and other birds) were the most common species observed as noted above. This makes sense given the importance of fish and waterfowl in the diet of circumpolar Indigenous groups (Donaldson et al., 2010; Furgal & Seguin, 2006; Nuttall et al., 2005). Therefore, other species that are not harvested or readily observed (e.g. aquatic insects) may not be equally reflected in recorded IK, resulting in limited observations surrounding certain groups of organisms. Nevertheless, there remains great potential for IK to play a role in continued freshwater biodiversity assessments and management of ecosystem changes. For example, this study demonstrates the importance of collaboration with IK for the implementation of any strategies to monitor and assess the movement and impact of invasive species.

In summary, this study demonstrated that IK provides valuable information towards determining Arctic freshwater biodiversity baselines and patterns of change. However, there is more to be learned from this rich and intricate knowledge base. It is recommended that future analysis of freshwater biodiversity, ecological condition, and patterns of change should explore Indigenous ways of life and thinking that take a more holistic worldview, integrating humans as a part of the ecosystem and considering the intrinsic interconnectivity among habitats (e.g. terrestrial, marine). A quote from an Indigenous Knowledge holder from the Hudson Bay (Canada) region captures this perspective: "Rivers and lakes contribute a lot to the well-being of people. You cannot make a decent living from land that has no water on it. The currents and rivers are the veins of Hudson Bay. They start from inside the basin and go out through Hudson Strait." (McDonald, Arragutainaq, & Novalinga, 1997; p. 64). Further understanding of Indigenous cultural worldviews around freshwater ecology would provide context to the knowledge collected and a more in-depth understanding of the Arctic circumpolar freshwater biodiversity and environments.

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CONFLICT OF INTEREST

The authors assert that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

All literature sources reviewed for the systematic literature search in this manuscript are listed in the Supplementary files (File S2).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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