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Abruptly and irreversibly changing Arctic freshwaters urgently require standardized monitoring

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Abstract

1. Arctic regions support a wide variety of freshwater ecosystems. These naturally oligotrophic and cold-water streams, rivers, ponds and lakes are currently being impacted by a diverse range of anthropogenic pressures, such as accelerated climate change, permafrost thaw, land-use change, eutrophication, brownification and the replacement of northern biota with the range expansion of more southern species.
2. Multiple stressors are rapidly changing Arctic freshwater systems as aquatic habitats are becoming more suitable for species originating from more southerly regions and thereby threatening biota adapted to cold waters. The livelihoods of Indigenous Peoples of the north will be altered when ecosystem services associated with changes in biodiversity are affected. Unfortunately, monitoring of biodiversity change in Arctic freshwaters is currently inadequate, making it difficult, if not impossible, to predict changes in ecosystem services.
3. *Synthesis and applications*. We propose a three-step approach to better address and facilitate monitoring of the rapid ecological changes that Arctic freshwater ecosystems are currently experiencing as a result of climate change. First, we should increase our efforts in the monitoring of freshwaters across all Arctic countries by setting up a network of monitoring sites and devoting more effort to a broad-scale baseline survey using standardized methods. Second, we should enhance modelling efforts to include both ecological change and socio-economic development. These models should help pinpoint species, ecosystems and geographical areas that are likely to show abrupt changes in response to any changes. Third, we should increase interaction among scientists, policymakers and different stakeholder groups. In particular, Indigenous Peoples must be involved in the leadership, planning and execution of monitoring and assessment activities

of Arctic freshwaters. The proposed approach, which is critical to detecting the effects of climate change in the circumpolar region, has broader applications for global coordination of Arctic freshwater biomonitoring. Through routine monitoring, standardization of methods, enhanced modelling of integrated scientific and socio-economic change, and increased collaboration within and among sectors, more effective monitoring and management of climate change impacts on freshwater biodiversity will be possible in the Arctic and globally.

KEYWORDS

Arctic, biodiversity, cold-water ecosystems, ecological change, freshwater, high latitudes, temporal change

1 | INTRODUCTION

Arctic regions support a wide variety of freshwater ecosystems which, in turn, may harbour surprisingly diverse biota. These ecosystems are currently in jeopardy. A recent report on Arctic freshwater biodiversity confirmed that Arctic ecosystems are experiencing alarming changes (Lento et al., 2019) and, worryingly, that the opportunities to gather baseline information on these understudied systems are rapidly disappearing. With continued Arctic amplification, which is the accelerated warming of Arctic regions due to factors such as shrinking sea ice cover (Serreze, Barrett, Stroeve, Kindig, & Holland, 2009), there is heightened urgency to develop a standardized means of monitoring rapid ecological change in these freshwater environments. In high-latitude freshwater systems, recent environmental changes are mainly driven by anthropogenic activities, particularly climate warming (Heino, Virkkala, & Toivonen, 2009), but also long-range transport of pollutants (Reid et al., 2019), land-use alterations and eutrophication and brownification, which have recently intensified in the Arctic (Hayden et al., 2019). While circum-Arctic regions have some of the largest remaining undammed river basins in the world (Grill et al., 2019), they comprise fragile riverine and lacustrine ecosystems with unique flora and fauna maintained through the interplay of ecological connectivity and environmental conditions (Kärnä et al., 2015). Even when connectivity remains high, climate warming jeopardizes the biodiversity of cold-adapted freshwater organisms, particularly in the High Arctic, as escaping to colder environments is no longer an option at these latitudes after temperature thresholds are exceeded.

With rapidly changing biodiversity, ecosystem services will simultaneously be altered, for example, through loss of fish species vital to subsistence harvesting. As a result, the livelihoods as well as the physical and cultural well-being of northern peoples will certainly experience radical changes in the near future (Lento et al., 2019). Reversing this trend may prove difficult, if not impossible, but better monitoring of freshwater biodiversity (e.g. species richness, distribution and abundance) and ecosystem services (e.g. fish production and recreational fisheries) may help model predicted changes and socio-economic impacts, as well as plan for and adapt to global environmental change. Although regional monitoring exists at small scales, ongoing work on polar biodiversity in general has highlighted a substantial lack of standardized monitoring data (Wilmotte & Erkinaro, 2019). Effective monitoring to support Arctic freshwater management requires scientists to forge stronger collaborations with policymakers, engage with different stakeholder groups, including Indigenous Peoples, and encourage greater local participation in monitoring efforts through citizen science initiatives. Understanding the links among environmental change (e.g. climate warming and landscape exploitation), biodiversity, ecosystem services and socio-economic aspects would also contribute to evidence-based solutions that can be implemented in the Arctic (Figure 1).

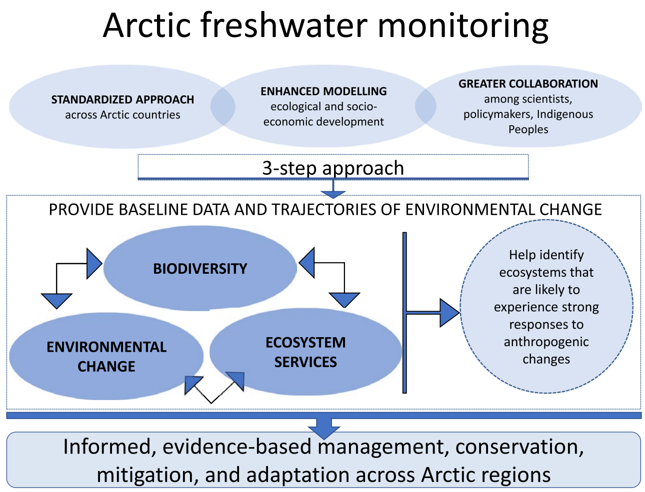

FIGURE 1 Advantages of increased monitoring of ecological change in the Arctic, benefitting from standardized monitoring, enhanced modelling and increased interaction among scientists and various stakeholder groups

2 | ECOLOGICAL CHANGES ARE RELATED TO HUMAN ACTIONS

The rate of human-induced climate warming at high latitudes significantly exceeds the global average (Larsen et al., 2014) because of a variety of climate feedback mechanisms leading to Arctic amplification (Pithan & Mauritsen, 2014). The past few years have registered the warmest Arctic temperatures on record (https://www.ncdc.noaa.gov/sotc/) and, in 2019, record-breaking summer temperatures were observed across the Arctic, including Greenland, Canada, Alaska and parts of Siberia. This contributed to the spread of extensive wildfires and unprecedented melting of the Greenland ice sheet (http://nsidc.org/greenland-today/). Permafrost thaw, resulting from increases in both temperature and precipitation (Kokelj et al., 2015), will have many consequences including higher loads of sediment and solutes affecting water quality (Kokelj et al., 2013), as well as jeopardizing infrastructure across large regions of the Arctic (Hjort et al., 2018). In addition to changes in abiotic conditions, climate warming has both direct and indirect impacts on the distribution and abundance of freshwater species (Heino et al., 2009) and the living conditions of Indigenous Peoples (Ford & Pearce, 2010). Entire aquatic ecosystems are disappearing from increased evaporation that has desiccated ponds (Smol & Douglas, 2007a) to drainage from permafrost thaw (Smith, Sheng, MacDonald, & Hinzman, 2005). Clearly, there is no single driver of ecological change. Rather, multiple stressors exacerbated by climate warming are threatening Arctic freshwaters (Lento et al., 2019), with ongoing ecosystem changes that are alarmingly rapid (Lehnherr et al., 2018). In addition, understanding how Arctic freshwaters are affected by anthropogenic change may be further complicated by interactions among different stressors, including 'ecological surprises'.

Arctic ecosystems are experiencing increased land-use pressures from a variety of anthropogenic activities including recent escalation in road construction, sand extraction from river banks, mineral extraction, hydropower generation and oil and gas exploration and production (Einarsson, 2014; Larsen & Fondahl, 2015). With continued climate warming, the potential for resource extraction and human development in the Arctic is expected to increase due to greater accessibility of remote locations. In addition, climate warming interacts with land-use alterations, such as the expansion of agriculture in the less remote regions of the Arctic, and through changes in natural vegetation with increasing coverage of shrubs and trees in tundra landscapes (i.e. 'greening' of the Arctic). Given the tight coupling of terrestrial and aquatic ecosystem processes (Wrona et al., 2016), these changes in land use and land cover will certainly alter freshwater environments.

Permafrost thaw, resulting from accelerated Arctic warming, produces increased inorganic sediment inputs to freshwater ecosystems through hill slope slumping that can increase (Thienpont et al., 2013) or decrease biodiversity (Chin, Lento, Culp, Lacelle, & Kokelj, 2016). For example, thaw slumps from permafrost degradation can introduce substantial levels of sediments to river systems causing significant declines in benthic macroinvertebrate abundance (Chin et al., 2016) and periphyton biomass (Levenstein, Culp, & Lento, 2018). Depending on run-off patterns, thaw slumps can also affect the chemistry and biota of lakes by increasing water clarity and productivity in these systems (Thienpont et al., 2013). These influences on Arctic freshwaters have been observed recently, but the likely widespread, rapid and ongoing nature of this phenomenon warrants increased attention and further studies (Lehnherr et al., 2018).

Increased nutrient concentrations in freshwater ecosystems linked to thawing permafrost or increased anthropogenic activities pose an ecosystem-level threat in many regions of the Arctic (Heino et al., 2009). Nutrient enrichment, coupled with decreased ice cover, results in increases in benthic primary production in rivers (Wrona et al., 2016) and a shift from primarily benthic to pelagic primary production in lakes (Rühland, Paterson, & Smol, 2015). Consequently, substantial changes in ecosystem function and community structure occur in the naturally oligotrophic high-latitude rivers, streams, lakes and ponds. Arctic freshwater ecosystems are becoming more productive, with greater macrophyte cover (Smol & Douglas, 2007b) and increased likelihood of algal and cyanobacterial blooms (Pick, 2016). Increases in primary producers will have concomitant effects on consumers and predators, ranging from zooplankton and benthic macroinvertebrates to fish and waterfowl. Such changes will inevitably result in re-organization of ecosystems and re-assembly of biological communities in Arctic freshwaters. Even in regions of the Arctic that are not experiencing nutrient increases, primary production has nevertheless increased over the past few decades, likely related to an extended growing season and warmer conditions (Smol & Douglas, 2007b). In fact, cyanobacterial blooms are now observed in Arctic lakes for the first time during extended periods of thermal stratification and have been linked to accelerated Arctic warming (Pick, 2016).

Brownification, caused by increasing concentrations of dissolved organic matter, is another major environmental change recently predicted to occur in Arctic freshwaters (Hayden et al., 2019). Like nutrient enrichment, it is partly a consequence of the joint effects of landscape alterations and climate warming in high latitudes. Brownification decreases water transparency, alters ecosystems processes and food webs, and ultimately affects fish production (Karlsson et al., 2009). This is of particular concern in High Arctic freshwaters that typically have clear waters.

3 | ABRUPT CHANGES ARE VISIBLE IN TEMPORAL DATA

Recent evidence from time-series and palaeoecological data suggests that Arctic freshwaters and their biota have experienced many rapid changes in response to climate warming. Arctic freshwaters could thus be considered harbingers of ecological change. These changes are clearly evident at different levels of biological organization, ranging from population genetics, species life-history patterns, abundance and distribution to community-level phenomena.

Anadromous fish have to cope with changing climate in highly variable environments during their life cycle, across long geographic distances and along a broad salinity gradient from freshwater to sea water. As a result, their life histories and the underlying genetics are responding to climate warming. Recently, an analysis of 40-year time-series data showed marked temporal trends in the life-history patterns of a large Atlantic salmon *Salmo salar* population complex in subarctic northernmost Fennoscandia (Erkinaro et al., 2019). In addition, the allele frequencies that are genetically controlling the age at maturity in the salmon populations have changed over the same period of time (Czorlich, Aykanat, Erkinaro, Orell, & Primmer, 2018). Moreover, climate change along with altered environmental conditions may lead to a mismatch between the environment and the phenology of habitat shifts in migratory fish. Long-term studies have suggested that Atlantic salmon smolts show a tendency to an earlier downstream migration to the ocean: migration timing across a large number of Atlantic and Baltic rivers is positively associated with increasing freshwater temperatures, with the initiation of the smolt migration occurring 2.4 days earlier per decade since the 1960s (Otero et al., 2014). This might affect salmon growth and survival through a temporal mismatch with the production of marine prey, causing reduced feeding opportunities, suboptimal ionoregulatory ability and resulting in delay in further migration, altered antipredatory behaviour and increased mortality (Otero et al., 2014).

Benthic macroinvertebrate communities have experienced interannual changes in subarctic lakes in Sweden. These changes are most evident in species richness which has increased over time in several lakes with sampling records of more than 10 years (Lento et al., 2019). On average, these long-term trends represent an increase in one species every 2–4 years. Even stronger increasing trends are evident since 2014 in high-latitude lakes in Sweden (north of 66°N). Given the strong spatial relationship between benthic macroinvertebrate diversity in the Arctic and temperature (Culp, Lento, Curry, Luiker, & Halliwell, 2019), these findings stress the value of long-term monitoring for detecting the ongoing change in the structure of freshwater communities.

Given that long-term observational data are rarely available in remote high-latitude regions, palaeolimnological archives from Arctic lakes and ponds can be used as a best-case alternative to direct monitoring and can provide a better understanding of the relationship between environmental change and ecosystem response over long time-scales. Dated sedimentary records of microfossil diatoms from lakes across the circumpolar Arctic show widespread and often threshold-type compositional change in response to recent warming that is unprecedented over recent centuries (Rühland et al., 2015) and likely millennia (Douglas, Smol, & Blake, 1994), including the world's most northerly lake (Perren et al., 2012). Indeed, the unprecedented amplitude of recent Arctic warming may be underestimated as recent palaeoecological evidence from plants entombed in receding ice caps indicate that Arctic summers over the past century are likely hotter than in any other century over the past ~115,000 years (Pendleton et al., 2019). The threshold-type ecological responses are particularly well expressed in Arctic sedimentary records because here even relatively small changes in ice-cover extent and duration have striking impacts on diatom growing conditions (e.g. development of new habitats, changes in thermal and mixing regimes, light and nutrients; Lehnherr et al., 2018; Rühland et al., 2015). Typical changes include higher aquatic production, an increase in diatom species diversity and marked shifts in their community composition, which often includes the establishment of planktonic taxa in deeper lakes (Rühland et al., 2015). In some regions, the 'final ecological threshold' has been crossed (Smol & Douglas, 2007a), with the complete desiccation of ponds and shallow lakes that have existed for millennia.

4 | WINNERS AND LOSERS IN THE FACE OF CLIMATE WARMING

Based on scenarios of biodiversity change across the Arctic, there will be an expected net increase in the number of species in Arctic areas, but with these gains, many other species will be lost (Heino et al., 2009). The gains comprise increased distributions and abundances of warm-adapted species, which can be considered as 'climate-change winners'. The losses will include local, regional or global extinctions of species that prefer cold-water environments and cannot migrate beyond the northern coasts to escape warming and competition with warm-adapted species. In addition, as many Arctic freshwater species have specific adaptations to withstand freezing conditions during the winter, such cold-adapted species may be particularly threatened by ongoing climate warming (Tolonen et al., 2019). Hence, cold-adapted species can be considered as 'climate change losers', resulting in an irreversible loss of unique Arctic biodiversity.

In addition to an increase in the numbers of species, 'climate-change winners' will dominate Arctic freshwater fauna and flora in the future. For example, northward range expansions of many species of freshwater invertebrates are expected once temperatures exceed lower-limit tolerance thresholds, resulting in higher invertebrate biodiversity at high latitudes (Culp et al., 2019). This change is already underway across the Arctic, with several warm- and cool-water species from more southern latitudes reported to have expanded their distributions northward. The clearest examples come from fish. For example, smallmouth bass *Micropterus dolomieu*, a predatory warm-water species, is expanding its range to high latitudes in Canada, thereby presenting a threat to cold-water fish species currently living in lakes there (Sharma, Jackson, Minns, & Shuter, 2007).

Cold-water species are retreating towards High Arctic areas, and may face a risk of extinction with further climate warming because they are already living on the edge. For example, Arctic charr *Salvelinus alpinus*, the northernmost freshwater fish species in the world and a staple in the diet of Indigenous Peoples living in the north, will certainly be among the losers in the face of climate warming (Lento et al., 2019). In some areas of the European Arctic, Arctic charr catch has already seen a long-term decline, whereas co-occurring species from the family Salmonidae, such as Atlantic salmon and brown trout *Salmo trutta*, have increased in numbers

(Lento et al., 2019). However, even these two fish species that are becoming more dominant are increasingly threatened by climate warming (Jonsson & Jonsson, 2009). There are certainly numerous similar loser species among freshwater groups other than fishes, but their distributions and abundances remain poorly monitored and documented in the Arctic.

5 | SHARING RESPONSIBILITIES TO UNDERSTAND ARCTIC ECOLOGICAL CHANGE

An extensive report on Arctic freshwater biodiversity was recently published by the CAFF-CBMP (Lento et al., 2019). The report was the product of the largest compilation and assessment to date of biodiversity data from the circumpolar Arctic region, involving expert networks from all Arctic countries. The main patterns and underlying mechanisms of biodiversity change in Arctic riverine and lacustrine environments were summarized, and tentative future change scenarios were proposed. However, devising these scenarios proved difficult by the lack of consistently collected monitoring data across broad regions of the Arctic. To date, most monitoring data have a limited spatial coverage (particularly in Canada and Russia), time series are of short duration, most existing efforts are focused on fish surveys or abiotic data collection, and most data are not strictly comparable because of differences in survey methods used across Arctic countries. However, even for fish, the existing data are inadequate, which is shown in spatial, temporal and taxonomic gaps in our knowledge (Laske et al., 2020). Thus, we propose a three-step approach to better address and facilitate monitoring of ecological change in Arctic freshwater ecosystems.

5.1 | Standardize monitoring

A major challenge for the future is to establish standardized monitoring of freshwater biodiversity across the Arctic countries. The CAFF-CBMP is working to develop and promote standardized protocols that are based on commonly employed methods in the Arctic, but it is necessary for monitoring agencies to recognize the importance of adopting such standardized methods to support circumpolar-scale assessments. It is also important to create international agreements that regulate the obligate, repeated reporting of monitoring data for Arctic riverine and lacustrine ecosystems. This can be facilitated through national and international agreements involving scientists, funding organizations, governments and the Arctic Council to establish a hub-and-spoke network of monitoring sites across the Arctic. Moreover, palaeoecological approaches can be used to dovetail between any available monitoring data and information contained in dated sediment cores. This is particularly important for remote regions where little or no monitoring data are available and establishing routine monitoring is cost-prohibitive.

5.2 | Enhance modelling

Future model-based predictions of climate change and its impacts on biodiversity and ecosystem services should consider both ecological change and socio-economic development. Using joint ecological and socio-economic models should help reveal species, ecosystems and regions that are likely to show abrupt changes in response to environmental change and pressures from socio-economic development in the Arctic. As Arctic regions are not only facing climate warming but also attracting increased interest from multi-national industries, scientists should harness their best science to pinpoint any alarming changes and propose avenues that contribute to sustainable development of Arctic ecosystems. Here, up-to-date interdisciplinary modelling approaches could be effectively used for planning policy and management actions. For example, the poor management of natural resources (e.g. fish populations threatened by climate change) has often resulted in the decline and, at times, the extirpation of populations (Bunnefeld, Hoshino, & Milner-Gulland, 2011). Therefore, it would be important to incorporate decision making by resource users into modelling, which would help guide conservation and management decisions.

5.3 | Increase interaction

Interaction among scientists, environmental administrations, fisheries managers, national governments, international policymakers via Arctic Council Working Groups, conservation organizations and especially Indigenous groups is also key to success. Policymakers should be made aware of the alarming trends of drastic ecological change across the Arctic, and that any socio-economic development that is planned should take into account the fragile nature of Arctic freshwater ecosystems. Indigenous Peoples of the north, whose lives are closely connected to the land, must be involved in the leadership, planning and execution of monitoring and assessment activities. Through their experience and knowledge of the land, Indigenous Peoples have a unique perspective on the ongoing change in Arctic landscapes that could support a more holistic monitoring of freshwater ecosystem change. Furthermore, there is an opportunity to work with Indigenous communities to provide them with the tools to take ownership over the monitoring of change in freshwater resources and the ecosystem services that are vital to their well-being.

6 | CONCLUSIONS

There is an urgent need for monitoring the ongoing abrupt and often irreversible ecological changes in Arctic freshwaters. These changes cannot be averted, but increased monitoring, modelling, interaction and planning is essential for conserving the most important features and services of these fragile ecosystems. Baseline data produced by monitoring programs will be vital for making better informed and realistic plans for the future. Such efforts can only be accomplished by joint engagement of all the Arctic countries, and an increased involvement of governments to provide funding to conduct monitoring and devise best possible predictions for understanding the future of Arctic freshwaters. These should also contribute to evidence-based solutions that potentially help protect, sustainably manage and conserve Arctic freshwater ecosystems.

AUTHORS' CONTRIBUTIONS

All authors contributed to the ideas and writing of this paper.

DATA AVAILABILITY STATEMENT

No data were used in this article.

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