1. Executive Summary

Introduction

Arctic freshwater ecosystems (lakes, rivers, and associated wetlands) are threatened by climate change and human development that can affect freshwater biodiversity. Such effects will change not only the distributions and abundances of aquatic species, but also the lives of Arctic Peoples that are dependent on the ecosystem services supplied by lakes and rivers. Thus, the freshwater biodiversity program of the Circumpolar Biodiversity Monitoring Program (Freshwater-CBMP) focuses on lake and river ecosystems and has established a long-term monitoring framework for these Arctic freshwaters. Developed for the Conservation of Arctic Flora and Fauna (CAFF; the biodiversity Working Group of the Arctic Council), this framework facilitates more accurate and rapid detection, communication and response to significant trends in Arctic water quality and biodiversity. Freshwater-CBMP goals are addressed in the *"Arctic Freshwater Biodiversity Monitoring Plan",* which describes an integrated, ecosystem-based approach for monitoring Arctic freshwaters (Culp et al. 2012a).

This State of Arctic Freshwater Biodiversity Report (SAFBR) is the first circumpolar assessment of key biotic elements, or ecosystem components, in Arctic freshwaters. The overall aim was to assess the current status and trends of freshwater biodiversity by geographical regions across the circumpolar Arctic. Specific objectives were to use existing monitoring data to: 1) assess alpha and beta biodiversity; 2) identify geographical locations with high biodiversity (i.e., biodiversity hotspots); 3) where possible, determine the primary environmental and human stressors associated with the observed changes in biodiversity; and 4) identify key monitoring locations for inclusion in future circumpolar assessments of ecological change in freshwaters.

The primary biotic elements examined were Focal Ecosystem Components (FECs), which are biotic assemblages that are ecologically pivotal and/or sensitive to changes in biodiversity and/or environmental conditions, and that are routinely monitored in the Arctic (e.g., fish, benthic macroinvertebrates, zooplankton, planktonic algae, algae from benthic samples, and macrophytes). Ecosystem changes that would affect biodiversity of FECs were placed in the context of testable impact hypotheses (or predictions). These impact hypotheses outline a cause-effect framework that describes how FECs are expected to respond to anticipated change in environmental and anthropogenic stressors. For example, permafrost degradation is expected to result in harsher physical disturbance regimes that increase sediment loads and turbidity of rivers. A full set of these impact hypotheses is listed in the Freshwater Biodiversity Monitoring Plan (Culp et al. 2012a).

Biodiversity was assessed using existing data for FECs gathered from all available sources (i.e., academia, government, industry, and documented Traditional Knowledge gathered from systematic literature searches) for the contemporary period (1950 to present), and where possible, for the post-industrial period (1900 to 1950) and historical (pre-1900) periods. Centralized data sources were available in national monitoring databases for some countries, but even in these cases (e.g., Sweden, Norway), considerable data formatting and harmonization were required before the data could be compiled for the circumpolar region. Consolidated databases were very limited in other countries, which induced extensive data searches and recovery of government reports, published literature and industry registries and digitization/harmonization before data could be added to the CBMP-Freshwater database. The extensive circumpolar freshwater database is a primary deliverable of the CBMP-Freshwater to CAFF, as it documents the underlying SAFBR data and will facilitate future assessments of change in Arctic freshwaters.

Abiotic Variables

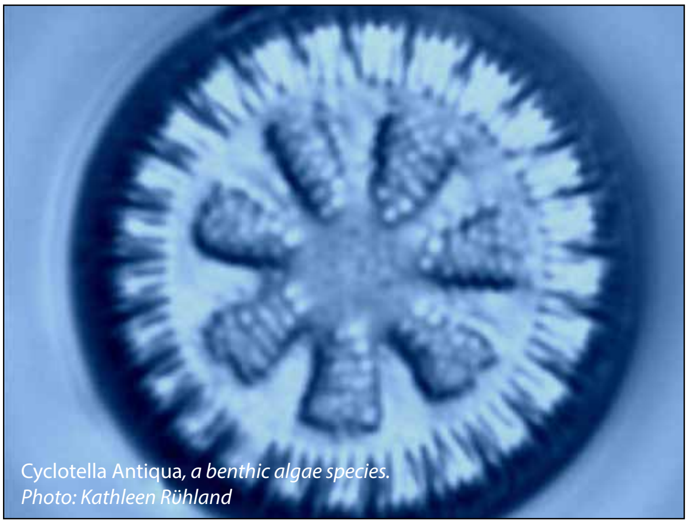
Lakes and rivers are closely interlinked with the surrounding landscape and reflect climate- and human-induced changes in land-use and development, with shifts in abiotic drivers of biodiversity being early warning indicators of ecological change. The Freshwater Monitoring Plan identifies nine major environmental and anthropogenic stressors to freshwater ecosystems that can be summarized as (1) permafrost thaw and changes in the hydrological regime resulting in higher loads of nutrients, solids, and organic matter; (2) long-range transboundary air pollutants and point source pollution originating from industrial development and urbanization; (3) fisheries over-harvesting; (4) climate-driven changes to riparian vegetation from grasses to shrub-dominated flora, i.e., greening of the Arctic; and (5) flow alterations and regulation due to hydropower dams and other forms of development that can lead to substantial habitat fragmentation and destruction. The Abiotic chapter of the SAFBR provides examples of long-term declines in ice-cover duration and increases in water temperature that have been observed in the Arctic. Long-term declines in total phosphorus concentrations are presented for major rivers in northern Sweden that illustrate the ongoing decline in freshwater nutrient concentrations (oligotrophication) of the Arctic/alpine regions of the Scandinavian Peninsula. In contrast to these slowly progressing changes are the rapid alterations of water turbidity and chemistry following the formation of permafrost thaw slumps, i.e., the collapse of landscape structures due to permafrost thawing. These examples highlight some of the various abiotic changes that are ongoing in Arctic landscapes and that affect water quality and biodiversity in lakes and rivers.

Scenarios of biodiversity change in Arctic freshwaters predict a net increase in biodiversity with warming temperatures, assuming dispersal routes exist for southern species to colonize northern regions. However, as water quality and habitat conditions shift to more closely resemble southern latitudes, this shift is expected to come with a reduction in the habitat range of cold-tolerant species endemic to the Arctic. In other words, along with an overall predicted increase in the number of species, there will be a net loss of unique Arctic-specific biodiversity. Alterations of habitat conditions originating from changes in air and water temperatures, permafrost extent, nutrient availability, and terrestrial vegetation will change the zonation of the Arctic region by globally decreasing the size of the sub-, low, and high Arctic regions, and by reducing habitats critical to cold-tolerant Arctic species. These alterations to aquatic biodiversity and food webs will ultimately induce changes to freshwater fisheries around the Arctic and to the ecosystem services that they supply to Arctic residents.

Biodiversity Assessment

Spatial patterns in diversity were assessed for each FEC for the circumpolar region by using a regionalization approach. Stations were grouped into climate-based terrestrial ecoregions, and patterns of alpha and beta diversity were evaluated within and among ecoregions. Alpha diversity (the number of taxa – species-level or higher, depending on the FEC) was assessed by using rarefaction curves to estimate taxonomic richness at a set number of stations within each ecoregion, in order to correct for variation in sampling effort across the Arctic. Comparisons of rarefied alpha diversity across ecoregions were used to assess broad spatial patterns. Beta diversity (change in species composition across stations) was assessed within ecoregions by grouping stations at a smaller spatial scale (hydrobasins, which are standardly-derived catchments) and estimating the relative contributions of turnover (replacement of taxa with new/different taxa across stations) and nestedness (with some stations containing a subset of the same taxa found at the richest stations) to beta diversity. Circumpolar and regional analyses were conducted on data with harmonized taxonomic names.

Algae from Benthic Samples



Cyclotella Antiqua, *a benthic algae species.*
Photo: Kathleen Rühland

Algae are key primary producers in Arctic freshwaters, and benthic samples include diatoms and a number of classes of other algal groups. This assessment focused on diatoms, as this is a major group in Arctic freshwaters and data availability was high. Lake diatom stations were the most evenly distributed across the circumpolar region of all the FECs, although coverage was patchy in Russia and lacking in the High Arctic of Greenland or Svalbard. The highest alpha diversity for lake sediments was found at low- to mid-level latitudes and in coastal ecoregions, including coastal Alaska, the Arctic archipelago and southern coast of Hudson's Bay in Canada, Iceland, and Norway. Beta diversity indicated that there was generally moderate to high dissimilarity in community structure among lake stations. Lake beta diversity was dominated by the turnover component in all ecoregions indicating that there was a high degree of species replacement across stations. The highest alpha diversity of river diatoms was in coastal Alaska and western Canada, and high diversity was also evident in Fennoscandian ecoregions. The lowest alpha diversity was found in eastern and southern Canadian ecoregions, which had on average half as many diatom taxa as in the most diverse ecoregions. Beta diversity within an ecoregion was highly variable for river diatoms, but turnover was the predominant component of beta diversity for river diatoms.

Samples with the highest diatom richness for both lakes and rivers were generally between 60-75°N latitude. However, the decline in richness outside this latitudinal range was small, and partly due to the fact that fewer samples were collected at the highest latitudes (above 75°N), particularly in rivers. Diversity was lower in the high Arctic than in the sub- or low Arctic, particularly for lakes, and analysis identified groups of taxa in both lakes and rivers that were characteristic of high latitude samples. Diatom taxa that were dominant across the circumpolar region are generally also common to other regions of the world. This is consistent with the observation that although temperature may affect diatom diversity, the distribution of species is also driven by local geology and water chemistry conditions. Many of the taxa found across the Arctic are typical of waters with low nutrient levels and neutral pH, although indicators for nutrient-rich conditions were also found. Assessment of paleolimnological data indicated that temporal change in diatom assemblage composition was lowest in the eastern Canadian Arctic, which has historically been subjected to less warming than other areas of the Arctic. Shifts in dominant taxa over time were indicative of strong community changes, likely due to changes in the thermal stratification regimes of lakes since circa 1800.

Lake diatoms are so far not generally included as part of routine monitoring programs, and thus assessment must rely on academic data. Although time series for these data are largely absent, the advantage of diatom samples in lakes is that long-term changes can be inferred from diatoms stored in sediment cores. However, the collection of cores should be expanded to a broader spatial area across the Arctic to facilitate broad-scale assessment of long-term trends for the circumpolar region. River samples were more sparse than lake samples, and were lacking from Russia, Iceland, Greenland, Svalbard, and central and western Canada. Although river algae monitoring is done routinely in some Arctic countries (e.g., Norway, Sweden, Finland), it is limited elsewhere in the circumpolar region. Furthermore, even in countries where monitoring occurs, the samples may not always be comparable if they focus on soft algae (non-diatoms, e.g., in Norway) or do not follow comparable sample processing procedures. Thus, there is a clear need to increase the spatial scope of river diatom monitoring in order to better capture biodiversity of this important group across the circumpolar region.

Phytoplankton

Achnanthes minutissima.
Photo: Chris Carter

Phytoplankton are microscopic algae that are suspended in the water column, and include diatoms and a number of non-diatom algal taxa. Assessment of rarefied alpha diversity within ecoregions indicated that phytoplankton diversity was highest in Fennoscandia and lowest in Russia and the Canadian High Arctic. Beta diversity was high in a number of ecoregions in Alaska, Russia, Fennoscandia, and southern Canada. Ecoregions in these areas showed the highest differentiation in phytoplankton assemblages and large among-lake differences in water body types (e.g., size/depth and water quality). Low and high Arctic lakes generally had higher beta diversity than sub-Arctic lakes. Turnover was the predominant component of beta diversity in all ecoregions, which is indicative of the introduction of new species across stations. This result suggests that spatially extensive monitoring of lake phytoplankton is required to provide reliable estimates of species turnover and biodiversity.

Cyanobacteria, which often include toxin-producing species, did not show long-term unidirectional trends in biovolume. However, there were similar peaks in Cyanobacteria biovolume across a number of lakes during years with high temperatures, with two-thirds of the Cyanobacteria peaks happening during one of the 10 hottest years on record. Since rising temperature and decreased ice cover potentially enhance cyanobacterial dominance (Paerl and Huisman 2008), continued monitoring of cyanobacteria in all Arctic regions may be useful in tracking associated climate and nutrient changes in Arctic water bodies. Long-term monitoring data for the full phytoplankton assemblage indicated a decrease in total biovolume in a highly productive lake in Greenland, while conversely, biovolume in a number of low productivity lakes in Finland and Sweden increased. If these trends continue into the future, phytoplankton biovolume will be expected to be more similar across these Arctic lakes.

Phytoplankton are not regularly monitored in all Arctic countries, therefore, data are patchy both in spatial and temporal coverage. The most extensive monitoring occurs in Fennoscandia and Greenland. In contrast, very little sampling occurs in the high Arctic and there is a need for increased monitoring across North America, Russia, and other northern areas of the Arctic. Future monitoring efforts for lake phytoplankton must improve consistency in sample processing methods, particularly with respect to the estimation of biovolume, and improve taxonomic resolution to the species-level where possible.

Polygonal lake, Khibiny mountains, Russia
Photo: Gregory A. Pozhvanov/Shutterstock.com

Macrophytes

Water milfoil (Myriophyllum alterniflorum)*.*
Photo: Mps197/Shutterstock.com

Macrophytes (macroscopic water plants) are primary producers that act as a food resource and supply habitat structure for other aquatic organisms. The highest alpha diversity of macrophytes was in Fennoscandian lakes. Alpha diversity was lowest at high latitudes and remote locations such as the Canadian High Arctic, Greenland, Iceland, and the Kola Peninsula. Three of the ecoregions with the lowest species richness had an average latitude > 70°N, suggesting that alpha diversity of macrophytes declines in high-latitude Arctic regions. The most common taxa across all stations were *Myriophyllum alterniflorum, Potamogeton gramineus,* and *Ranunculus reptans.* Aquatic moss species comprised a higher percentage of total species richness with increasing latitude.

For most ecoregions, turnover was the dominant component of beta diversity as it accounted for more than 70% of the total beta diversity. This indicates that variation in diversity within an ecoregion was due to finding different species across stations, and emphasizes the importance of increasing sample coverage. Beta diversity of macrophyte assemblages ranged between 0 (no inter-station differences in species composition) and 1 (no inter-station overlap in species) within the ecoregions. Macrophyte beta-diversity was largely driven by ecoregion connectivity, with remote ecoregions generally having lower beta diversity.

Extensive macrophyte data were available for some areas of the Arctic (e.g., Fennoscandia), but data were sparse for large areas of Canada, Alaska, and Russia. Macrophyte monitoring is not part of regular assessments in Canada, Alaska, and Russia, thus limiting the spatial scope of available data. Across the entire circumpolar region, there are very few lakes that are monitored regularly. As a result, time series data are generally not available, and many lake observations are outdated (e.g., 1970s or earlier) with no repeated visits to the same lakes. Such data do not allow for the detection of shifts in macrophyte distribution and may not provide an accurate view of contemporary patterns in diversity. Moreover, monitoring may not include the identification or enumeration of aquatic mosses, helophytes, or bryophytes, which may be of particular concern if these groups are dominant in a region, as often occurs in the sub- and high Arctic. Improvements to the monitoring of macrophytes are necessary across the circumpolar region, and should focus on regular and repeated monitoring of representative lakes with standardized monitoring protocols.

Zooplankton

Daphnia longispina.
Photo: Deiter Ebert

Zooplankton are microscopic invertebrates that live suspended in the water column and provide an important food source for fish in lakes. Zooplankton include crustacean taxa and rotifers, the latter of which are often not identified in samples. Crustacean zooplankton showed the highest alpha diversity for lakes in northern Russia, Fennoscandia, and Alaska. A limited set of stations with rotifer information indicated that rotifers added a small to moderate number of taxa to regional zooplankton diversity. Assessment of the full zooplankton assemblage provided evidence of high alpha diversity in coastal regions, particularly in Fennoscandia, Russia, and Alaska. This pattern is consistent with predictions that high richness would be found in areas that were unaffected by recent glaciation (e.g., Alaska) and in coastal areas (Rautio et al. 2008, Samchyshyna et al. 2008).

Beta diversity of zooplankton (crustaceans and rotifers) varied, with some ecoregions in Alaska, Russia, and Fennoscandia indicating high assemblage differences among lakes, and other ecoregions in the high Arctic or where few lakes were sampled indicating low differences in species composition among lakes. These findings highlight the importance of monitoring zooplankton in a wide variety of lakes within an ecoregion, to ensure the full diversity in an ecoregion is captured. Diversity was generally dominated by species turnover in ecoregions where more lakes were sampled over a wider spatial extent. Consequently, widespread sampling would be necessary to accurately summarize the full diversity of species in an area and ensure differences among lakes were captured.

The most diverse groups in the zooplankton dataset were the calanoid copepods, cyclopoid copepods, cladocerans, and rotifers. Common species of rotifers and crustaceans are also common and abundant outside the Arctic. Cladocerans were numerically dominant in sub-Arctic lakes (approximately 50% of all specimens), however, this group decreased in the presence of cyclopoid copepods in the low Arctic and high Arctic. The relative abundance of calanoid copepods was similar between the sub-Arctic and low Arctic, and declined in the high Arctic zone. Ongoing climate change may provide opportunities for the spread of Eurasian species, such as Bythotrephes longimanus and Limnosida frontosa, to the North American continent and lead to potential shifts in biodiversity and food web structure.

Greenland and Norway are the primary regions with routine monitoring at established stations for zooplankton, whereas data from other regions often come from environmental impact studies (e.g., Canada) rather than long-term programs intended to evaluate natural variation or monitor for effects of climate change. The lack of data in some European countries may be due to the fact that zooplankton are not considered an *"ecological quality element"* according to the European Water Framework Directive and thus have lower priority in monitoring. The necessary reliance on data from academia, industry, or other non-governmental organizations means that there are few time series, and in some areas, limited sampling of the full zooplankton assemblage (e.g., areas with research focused on Crustacea or just on cladocerans or copepods). Future monitoring efforts should be based on a set of permanent monitoring sites covering all climatic regions in each country, with an aim to standardize collection methods and the habitats sampled.

Benthic Macroinvertebrates

Ephemeroptera (top) and Heptageniidae (bottom)
Photo: Jan Hamrsky

Benthic macroinvertebrates are macroscopic invertebrates (predominantly insects) that live on the bottom of lakes and rivers and provide an important food source for fish. Alpha diversity of lake littoral (near-shore) habitats showed strong regional differences, with the lowest alpha diversity in remote areas and islands (e.g., Greenland, Iceland, Faroe Islands, Wrangel Island) and the highest taxonomic richness in Fennoscandia and the coastal regions of Alaska. Similarity in diversity estimates for the most taxonomically-poor ecoregions suggests that barriers to dispersal, such as proximity to mainland and presence of mountains, limit biodiversity in these northern lakes. Beta diversity within ecoregions was variable, with a higher importance of species loss evident in remote island ecoregions. Macroinvertebrate diversity in the lake profundal (deep water) zone habitat was lower and less variable than littoral zone observations; nevertheless, circumpolar trends showed a similar pattern.

Alpha diversity of river macroinvertebrates was lowest at the highest latitudes and on remote islands (e.g., Canadian high Arctic, Svalbard, Greenland, Iceland, Wrangel Island). Diversity also appeared to be lower in mountainous ecoregions. Conversely, the highest alpha diversity was observed at the lowest latitudes on the mainland where connectivity does not affect dispersal of taxa from southern regions and thermal regimes are the warmest. Beta diversity for rivers was high within all ecoregions, and taxonomic nestedness (loss of species) contributed more to beta diversity in high latitude, high altitude, and remote island ecoregions.

Further analysis of alpha diversity in lakes in rivers in relation to latitude indicated a strong latitudinal decline in both rivers and lake littoral zones above 68°N. Declines were likely a result of high-Arctic environments exceeding the thermal tolerances of taxa. In rivers, variability in this pattern at the mid-latitudes was associated with a west-east temperature gradient that exists in North America and colder thermal regimes in the eastern Canadian Arctic relative to similar latitudes in Fennoscandia. Lower diversity was also evident where dispersal was limited. This was particularly evident in lakes located on islands, where diversity was consistently lower than mainland stations, even at similar latitudes.

Monitoring gaps for benthic invertebrates of lakes and rivers are largely related to the need for harmonized sampling design and method. River benthic macroinvertebrate data were among the most extensive of all FECs with good spatial coverage across the circumpolar region, and with a relatively standardized sampling method. However, single-event sampling of riverine macroinvertebrates was common, and with the exception of Sweden, time series data were scarce. In lakes, there were large gaps in the spatial coverage of benthic invertebrate data due to a lack of routine monitoring in many areas, and because the sampled habitats (e.g., near-shore vs. deep-water zones, which have different assemblages of benthic macroinvertebrates) and sampling methods varied by country. To support future macroinvertebrate assessment in lakes, countries need to standardize the sampling approach, ideally including sampling of the taxonomically-rich littoral habitat. An additional limitation to the strength and scope of diversity assessment for both rivers and lakes is the current inconsistency in the taxonomic resolution, particularly for midges (chironomids), which are predominant in the Arctic. Future assessments should continue to make use of the strong spatial coverage of data and accessibility of data from national databases, but monitoring activities must include higher taxonomic resolution of the Chironomidae (i.e., to sub-family using microscopic techniques or to species-level using genetic barcoding) and schedule regular re-sampling of areas to establish the time-series data required to assess the impacts of climate change and development.

Chukotka, far east Russia
Photo: Sergey Pergat/Shutterstock.com

Sarek National Park, Jokkmok, Sweden"
Thomas Bresenhuber/Shutterstock.com

Fish

Arctic Char
Photo: Dan Bach Kristensen/Shutterstock.com

Freshwater fish are ecologically, socially, and economically important in the Arctic, and more information is known about the distribution and diversity of fish species in Arctic lakes and rivers than is known about other FECs. Within the ecoregions included in this assessment, 100 fish species are known to occur. Large-scale alpha diversity varied among ecoregions, ranging from a single species in the high Arctic to as many as 47 species in Fennoscandia. Fish alpha diversity varied across continents with northern and mountainous ecoregions having lower diversity. Islands (e.g., Iceland, Greenland) had fewer fish species due to biogeographic constraints.

Fourteen species of fish had a distributional range across continents - including salmonids, smelts, sticklebacks, freshwater cod, pike, and lamprey. Three additional species (all Salmonids) have been introduced to Fennoscandia and Russia from North America. Longitudinal distribution patterns of fish species showed a marked decline in the Atlantic zone, from generally more than 50 species in North America to many stations with less than 50 species in Fennoscandia. Our analysis also showed that alpha diversity at latitudes above 72°N declined to a single species, Arctic charr, although more species are known to occur.

Beta diversity differed across ecoregions, with higher values in Alaska and inland Fennoscandia. The turnover component of beta diversity was dominant in ecoregions in these areas. This indicates that the replacement of species across spatial or environmental gradients drives diversity patterns across a range of ecoregion types in North America and Fennoscandia, including alpine and taiga habitats. The nestedness component of beta diversity was greater only in Iceland, where only three species were represented in the data, and changes in species composition across the region would result from sub-setting the richest fish community.

While fish are key species in aquatic ecosystems and are important to communities of the North, it is evident that there are significant gaps in monitoring effort and data coverage across the circumpolar region. Although in some cases the spatial extent is limited because existing datasets were not accessible, there remain significant gaps in monitoring effort and coordination of routine monitoring in some areas. Across Canada, for example, a large number of historical studies focused on monitoring commercial or subsistence fisheries, and thus quantified a selection of fish species rather than assessing the diversity of the full assemblage. Furthermore, many sites across North America have only been sampled one time, thus precluding temporal analyses of trends. Similarly, there are large areas that have not been sampled sufficiently to allow for analyses of spatial patterns or temporal trends. Until broader spatial and temporal data coverage is available, the ability to assess changes in biodiversity, especially at large spatial scales, will be limited.

Freshwater Biodiversity Synthesis

Warming temperatures in Arctic rivers and lakes will likely lead to an increase in biodiversity as southern species expand their range northwards, and cold stenotherms are extirpated from waters that exceed their thermal tolerance threshold. Where cold-water endemic species are limited to the Arctic region, this will result in global losses of these species, e.g., for fish such as Arctic charr. A warmer and wetter climate will also increase rates of mineral weathering, decomposition of soil organic matter, erosion and sedimentation. This likely will lead to higher concentrations of organic matter, minerals, and nutrients. Such change in key drivers of the freshwater environment can affect large-scale processes (e.g., brownification, nutrient enrichment, sedimentation) of lake and river ecosystems leading to changes in alpha and beta diversity and ecosystem productivity.

We compared spatial diversity patterns among FECs to identify areas of the Arctic with consistently high or low diversity. Fennoscandian lakes represented a diversity hotspot for macrophytes, zooplankton, benthic macroinvertebrates, and fish. The warmer climate in Fennoscandia and strong connectivity to the mainland may play a role in the overall high diversity of the area. The coastal ecoregion in Alaska and western Canada ranked as the most diverse for lake diatoms and phytoplankton, and one of the most diverse ecoregions for lake fish. Connectivity of the Alaskan coastal region and lack of recent glaciation in that area may have contributed to high diversity of lake diatoms, phytoplankton, and fish. Ecoregions in Canada, Greenland, and Iceland were generally less diverse for many of the lake FECs.

Similar results were obtained when the diversity of river FECs were compared across ecoregions. Fennoscandia was overall the most diverse region across diatom, benthic macroinvertebrate, and fish FECs, though the coastal ecoregion in Alaska and western Canada showed the highest diversity of diatoms and fish. As observed for lakes, river diversity in the mountainous ecoregions of Alaska and western Canada was low, suggesting an impact of harsh environmental conditions associated with higher elevations. Alaskan ecoregions south of the Brooks-British Range ranked low for fish diversity, possibly reflecting the effect of dispersal barriers to anadromous species immigrating from the diverse Arctic Coastal Tundra. Eastern and northern Canada, which have colder long-term average temperatures than western North America or Fennoscandia, had the lowest diversity of river diatoms and benthic macroinvertebrates.

Regional evaluations of the relationships between FECs and environmental drivers revealed the importance of temperature as an overriding driver for multiple FECs in both lakes and rivers. For example, latitudinal and longitudinal patterns in river benthic macroinvertebrates reflect temperature gradients across the North American Arctic. Other factors related to dispersal, glaciation history, and bedrock geology were also identified as important drivers of diversity in North American river FECs. In Fennoscandia, FECs in lakes were strongly influenced by climatic drivers (e.g., latitude, temperature, precipitation) and vegetation cover. The drivers in both regions include both large-scale, slowly progressing landscape-level processes that will have long-lasting effects, as well as rapid modifications which have more local and short-term effects. The concerted action of these environmental drivers, and their subsequent effects on biological assemblages, will depend on regional conditions. Slow response times will make some of these processes progress for decades to come, while others may induce sudden biological shifts with strong repercussions on aquatic ecosystems when critical threshold levels are exceeded. These analyses form the baseline against which future assessment can be compared, and begin to address some of the impact hypotheses in the freshwater biodiversity monitoring plan (Culp et al. 2012a).

Reciever station for underwater loggers, Zackenberg NE Greenland
Photo: Kirsten S. Christoffersen

State of Monitoring and Advice

Chapter 6 of the SAFBR provides an overview of ongoing freshwater monitoring activities in the Arctic countries and summarizes the various parameters measured in the Arctic countries. This overview illustrates the large differences in the organization of monitoring by the each country, the FECs monitored, and the spatial coverage of monitoring in the Arctic. We demonstrate that the availability and coverage of data varied among the Focal Ecosystem Components. Lake ecosystems are not routinely monitored for many FECs in large countries such as Russia, Canada and the US because monitoring is dependent on irregular or insecure funding. However, Canada, Greenland, and Iceland have a monitoring focus on fish monitoring. In contrast, the Fennoscandian countries have well-established monitoring programs for lake FECs based on secure funding (e.g., Water Framework Directive) although the spatial coverage is poor for some FECs. Monitoring of river FECS shows a similar trend except that Canada routinely monitors the benthic macroinvertebrate and fish FECs. In general, the Arctic countries monitor abiotic parameters in rivers to a much greater extent than in lake ecosystems.

Freshwater biomonitoring has traditionally focused on the assessment of ecosystem health and pollution-effects, and has used standardized sampling effort and sample processing to reduce observation variability and increase ability to detect ecological change. While this type of monitoring can be used to estimate biodiversity, these techniques are not designed to measure the full biodiversity of a site because they can underestimate the presence of rare species. Future monitoring must focus on harmonized methods, with sampling in a sufficient number of stations across representative ecoregions to support the detection of trends related to testing impact hypotheses. Chapter 6 suggests a number of improvements for future monitoring in the Arctic that build on the long tradition of bioassessment in freshwaters and that include community engagement. More specifically, we provide the following key recommendations for consideration in future biodiversity monitoring of freshwater ecosystems in the Arctic:

Emerging Approaches

- Incorporate Traditional Knowledge as an integral part of future circumpolar monitoring networks.
- Engage local communities in monitoring efforts through Citizen Science efforts.
- Include an increased focus and use of remote sensing approaches.
- Make use of recent advances in environmental DNA (eDNA) methods and genetic barcoding.

Future Monitoring Methods

- Further harmonize sampling approaches among countries, and select appropriate sampling methods and equipment to balance between maintaining consistency and comparability with historical data and alignment with common methods used across the circumpolar region.
- Develop supplementary monitoring methods that provide better standardized estimates of biodiversity to maximize the likelihood of detecting new and/or invasive species.
- Use a regionalization approach based on ecoregions to guide the spatial distribution of sample stations and, ultimately, to provide better assessments.
- Ensure that spatial coverage of sampled ecoregions is sufficient to address the overarching monitoring questions of the CBMP across the circumpolar region, maintain time series in key locations, and fill gaps where monitoring data are sparse.
- Ensure the number of monitoring stations provides sufficient replication within ecoregions and covers common water body types.

Future Monitoring Design and Assessment

- Arctic countries should establish a circumpolar monitoring network based on a hub-and-spoke (intensive-extensive) principle in remote areas.
- Experimental design for the hub-and-spoke network should largely focus on addressing the Impact Hypotheses developed in the CBMP freshwater plan to increase focus on assessing biotic-abiotic relationships in Arctic freshwater systems.
- The Freshwater Steering Group of the CBMP should continue to serve as the focal point for the development and implementation of pan-Arctic, freshwater biodiversity monitoring.
- There should be a focus on continuing monitoring efforts at stations with existing time series, as these stations form key sites for future evaluations of temporal changes.
- Resources must be provided to maintain and build the freshwater database for future assessments in order to maximize the benefits of this database
- Arctic countries should make better efforts to document and preserve data from short-term research projects and research expeditions, as well as from industrial, university and government programs.
- Due to the patchy nature of sampling, future assessments require the continued use of rarefaction curves for scientifically-sound comparisons of alpha diversity across ecoregions.

Considering the rapid changes occurring in Arctic ecosystems, there is an urgent need for the CBMP-Freshwater of CAFF to continue building baseline databases to aid the assessment of future biodiversity change. In addition, harmonization of monitoring efforts among Arctic countries and a greater focus on Arctic lakes and rivers should be a strategic goal. Lastly, we stress that status assessments of Arctic lakes and rivers must explore the close association of biodiversity with spatial patterns of physico-chemical quality of aquatic habitats that can drive biological systems.