Landmannalaugar, Iceland
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2. Introduction

2.1. Monitoring Freshwater Biodiversity in a Changing Arctic

The State of Arctic Freshwater Biodiversity Report (SAFBR) is the first Circumpolar Biodiversity Monitoring Program (CBMP) assessment to summarize the status and trends of key biotic elements, or Focal Ecosystem Components (FECs), in the Arctic freshwater environment. The assessment used existing data for FECs gathered from all available sources (i.e., academia, government, industry, and documented Traditional Knowledge collected through systematic literature searches) to improve the detection and understanding of changes in circumpolar freshwater biodiversity. The CBMP-Freshwater effort represents the first international initiative to develop an integrated, ecosystem-based approach for monitoring Arctic freshwater biodiversity.

Although Arctic freshwater ecosystems have been defined by the CBMP as rivers, streams, lakes, ponds, and their associated wetlands (Culp et al. 2012a), this assessment focuses only on rivers, streams, lakes, and ponds due to a lack of monitoring data for wetlands. These environments are threatened by climate change and human development that can affect freshwater biodiversity (Wrona et al. 2013). Climate-related increases in air temperatures can thaw permafrost, change ice cover regimes, increase growth and spatial coverage of terrestrial vegetation (e.g., shrubification), and modify hydrological processes including water balance. In glacially-fed systems, climate change is expected to lead to significant changes in community structure and function along down-stream longitudinal gradients as the loss of glaciers affects hydrological and thermal regimes of receiving waters (Milner et al. 2017). Biodiversity shifts in Arctic regions may cause more significant changes to ecosystem function than in lower latitudes because of the low functional redundancy in these remote locations (Post et al. 2009), as warming and glacial retreat are expected to lead to increases in species richness in concert with increased functional diversity (Brown and Milner 2012, Brown et al. 2018). Overall, the distributions and abundances of freshwater species in Arctic freshwaters, as well as the lives of Arctic Peoples, are expected to be altered in response to such environmental regime shifts (see section 3.3).

2.2. The Circumpolar Biodiversity Monitoring Program (CBMP)

The CBMP is the cornerstone program of the Conservation of Arctic Flora and Fauna (CAFF; the biodiversity Working Group of the Arctic Council), and is organized into Marine, Freshwater, Terrestrial, and Coastal ecosystem groups that develop CBMP monitoring plans and authoritative assessments. The program was developed to improve long-term monitoring of Arctic biodiversity to facilitate more rapid detection, communication and response to significant trends in biodiversity, and to identify the factors driving those trends (Barry et al. 2013). It is an international network of scientists, governments, indigenous organizations, and conservation groups working to harmonize and integrate efforts to monitor the Arctic's living resources. This adaptive monitoring program incorporates management questions, conceptual ecological models, experimental monitoring design, data collection and reporting. In addition, the CBMP aims to gather data from both Traditional Knowledge (TK) and science, and make this information more readily available to policy-makers and the public in order to improve conservation and management of the Arctic's natural resources. The design adopted by the CBMP follows the steps required for an effective and adaptive scientific and ecosystem-based monitoring program (Lindenmayer and Likens 2009), and includes a consideration of what future priority questions and user needs should be addressed by the program (Figure 2-1). Future questions will be guided by the CAFF Board and other Arctic biodiversity data users (Barry et al. 2013, Christensen et al. 2018).

Disko field work
Photo: Kirsten S. Christoffersen

2.3. The Arctic Freshwater Biodiversity Monitoring Plan

CBMP goals for freshwater ecosystems were addressed by the Freshwater Expert Monitoring Group (CBMP-Freshwater) who developed an integrated, ecosystem-based approach for monitoring Arctic freshwater biodiversity (Culp et al. 2012a). The monitoring principles followed the current practice of assessing the distribution and abundance of biota (i.e., biodiversity) in relation to the physical and chemical environmental conditions of freshwater ecosystems. The plan details the rationale and framework for monitoring circumpolar Arctic freshwaters with the aim of harmonizing freshwater biodiversity monitoring activities across the Arctic countries. It is designed to increase the spatial and temporal extent of monitoring data and improve monitoring in Arctic freshwaters where representative biological data sets and long time series are mostly lacking. Data from these programs can be used over the long-term to produce status and trend assessments for Arctic freshwaters. An intent of this approach is to stimulate future research initiatives to improve predictions for environmental change in Arctic freshwaters, facilitate implementation of long-term monitoring strategies, and improve reporting on the state of Arctic freshwater ecosystems. The use of TK should be increased in the future because, to date, TK has received limited attention as a result of limited funding support and human capacity.

2.3.1. Arctic freshwater ecosystems

Freshwater ecosystems are an integral part of Arctic landscapes. For example, some 121,000 lakes are found within the land mass defined by the CAFF-boundary (Figure 2-2), of which 68% are situated in Canada and 21% in Russia. Among the Arctic countries, lakes on average cover 3.7% of the land area (range 0.5 on Greenland to 8.8 in Canada), stressing their importance in Arctic landscapes. Lake and river ecosystems reflect changes and activities in their catchments, thus these systems and their biota can be used to detect ecological shifts at large spatial scales. Freshwater biodiversity for this assessment was evaluated within the Arctic Biodiversity Assessment (ABA) and CAFF spatial boundaries, with the Arctic divided into sub-regions (high Arctic, low Arctic, sub-Arctic; Figure 2-2). These Arctic sub-regions cover a wide range of biomes from glaciers and permafrost areas to northern forests, have relatively uniform biogeographical characteristics and are typically characterised by low biodiversity and relatively simple food webs. Assessments of individual Focal Ecosystem Components (FECs; see section 2.3.2) were conducted at a circumpolar as well as at the country or regional scale. Several countries were grouped within regional subdivisions based on geographic proximity (i.e., North America, Fennoscandia including Svalbard).

2.3.2. Focal Ecosystem Components and Impact Hypotheses

Focal Ecosystem Components (FECs) are biotic taxa that are ecologically pivotal, charismatic and/or sensitive to changes in biodiversity and/or environmental conditions. Arctic freshwater experts chose the most representative FECs to be used as practical indicators of Arctic freshwater ecosystem health. Expert consensus identified these FECs as central to the functioning of an ecosystem, sensitive to potential stressors, and most likely to be commonly represented in existing databases for the circumpolar Arctic (Table 2-1). For example, although microbial assemblages are important for biogeochemistry of freshwaters, they are not routinely monitored in the Arctic and thus cannot be assessed across the circumpolar region at this time. FECs are placed in the context of expected ecosystem change through the development of testable impact hypotheses (or predictions) that outline a cause-effect framework regarding how change in environmental and anthropogenic stressors is expected to affect FECs. A full set of impact hypotheses has been described in the Freshwater Biodiversity Monitoring Plan (Culp et al. 2012a). For example, permafrost degradation is expected to result in increased sediment loads and turbidity of rivers (i.e., Sediment Regime Change), thus negatively affecting the light and physical disturbance regimes of rivers. More examples of impact hypotheses that specifically act on the various FECs are given in section 3. Testing of these hypotheses requires targeted assessments that are designed to detect impacts of the stressors of interest, or long time-series that can indicate temporal stressor-response patterns. As such, it may not be possible to test all of the impact hypotheses with the data that have been collected for this report (e.g., hydrologic regime changes due to flow regulation or glacial retreat). However, assessment of the current status of biodiversity across the Arctic provides a baseline with which future data can be compared, and the impact hypotheses provide both guidelines for future scientific data collection and a focus for management decision-making.

Table 2-1 Biotic Focal Ecosystem Components (FEC) selected for inclusion in Arctic freshwater monitoring and assessment.

Focal ecosystem Component	Ecosystem
Fish	Lakes and rivers
Benthic Invertebrates	Lakes and rivers
Benthic agae	Lakes and rivers
Zooplankton	Lakes
Phytoplankton	Lakes
Macrophytes	Lakes

A list of indicators previously used in freshwater monitoring was considered for the assessment of FECs, however, taxa presence/absence and abundance (numerical and biomass) were chosen because they provided the maximum coverage across the Arctic (Table 2-2). The indicators used built on those employed by the Marine Expert Monitoring Group (Gill et al. 2011) with key criteria being that they were: 1) sensitive to environmental change and anthropogenic stressors; 2) scientifically valid and relevant; and 3) likely to be monitored into the future. These parameters allowed estimation of several indicators of ecological structure, including alpha diversity and beta diversity.

Figure 2-1 The CBMP takes an adaptive Integrated Ecosystem based Approach to monitoring and data creation. This figure illustrates how management questions, conceptual ecosystem models based on science and Traditional Knowledge (TK), and existing monitoring networks are designed to guide the four CBMP Steering Groups (marine, freshwater, terrestrial, and coastal) in their development. Monitoring outputs (data) are designed to feed into the assessment and decision-making processes (data, communication and reporting). The findings are then intended to feed back into the monitoring program.

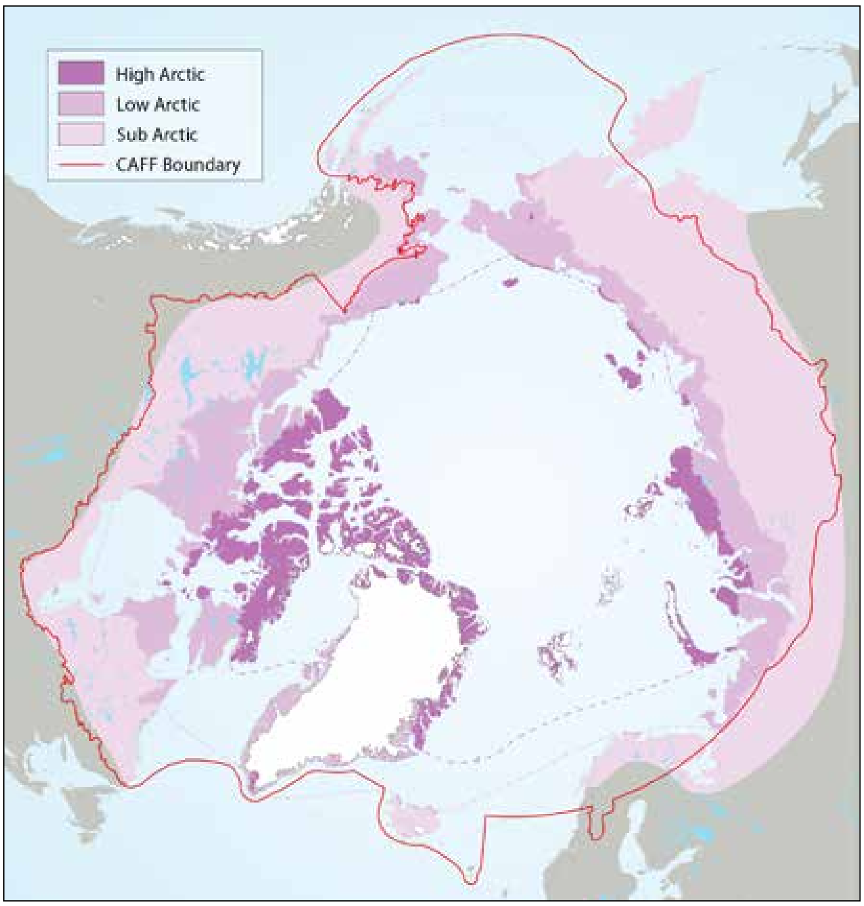

Figure 2-2 Arctic freshwater boundaries from the Arctic Council's Arctic Biodiversity Assessment developed by CAFF, showing the three sub-regions of the Arctic, namely the high (dark purple), low (purple) and sub-Arctic (light purple), and the CAFF boundary (red line).

Table 2-2 List of monitored parameters for Focal Ecosystem Components (FECs) and the list of potential indicators and indices for each FEC in lake and river ecosystems. For the State of Arctic Freshwater Biodiversity Report, the most widely available data for Arctic freshwaters included information on taxa presence/absence and taxa abundance (numerical and/or biomass). The ecosystem to which each FEC applies can be found in Table 2-1.

FECs	Monitored	Indicators/Indices
Benthic algae and phytoplankton	Number of individuals or biomass of each taxon	Community indices (e.g., abundance and density, taxonomic richness, diversity and dominance, biomass and numbers of keystone taxa)
		Numbers of red-listed (endangered) and rare taxa
		Distribution and range (e.g., latitudinal and altitudinal)
	Biomass (including chlorophyll a and biovolume)	Bulk algal biomass
		Size structure of entire population or of keystone taxton
Fish, benthic macro-invertebrates and zooplankton	Number of individuals or biomass of each taxon	Community indices (e.g., abundance and density, taxonomic richness, diversity and dominance, biomass and numbers of keystone taxa, ecological traits)
		Numbers of red-listed (endangered) and rare taxa
		Distribution and range (e.g.,latitudinal and altitudinal, residency/anadromy for fish)
	Genotypes and alleles (fish)	Genetic diversity
	Biomass (including biovolume, length, and weight)	Size structure of an entire population or of keystone taxton
	Age of individuals	Age structure of entire population or of a keystone taxon; growth rates (size at age or age at length (fish), or life cycle stage at length (BMI) and age at maturity (age combined with biomass)
	Timing of key life history events	Migratory phenology
		Emergence timing
	Body burden of key contaminants in fish	Concentrations of contaminants in fish tissues above consumtion guidelines or above environmental thresholds for sub-lethal or lethal effects
Macrophytes	Areal cover of each taxon	Community indices (e.g., abundance and density, taxonomic richness, diversity and dominance, biomass and numbers of keystone taxa, ecological traits)

2.3.3. Global Linkages of Freshwater CBMP

The size and nature of Arctic ecosystems make them critically important to the biological, chemical and physical balance on a global scale (Meltofte 2013). Therefore, CAFF makes significant efforts to develop strategic partnerships and ensure that Arctic biodiversity information provides added value to other Arctic Council and related global activities and forums. This approach helps CAFF contribute to the attainment of global biodiversity goals, targets and commitments of biodiversity-related Multilateral Environmental Agreements (MEAs) and other relevant international biodiversity forums. For example, CAFF has a framework of agreements with the biodiversity MEAs that are relevant to the Arctic, e.g., Ramsar and the Convention on Biological Diversity (CBD) (Meltofte 2013). Furthermore, CAFF is undertaking work focused on enhancing engagement in relation to the roles and functions of Arctic wetlands as a resource for humans and biodiversity to support sustainable development and resilience in the Arctic. CAFF also has the Arctic Migratory Bird Initiative (AMBI), which aims to improve sustainability of populations of migratory birds that breed and make use of freshwater ecosystems in the Arctic.

The CBMP is endorsed by the Arctic Council and the United Nations Convention on Biological Diversity (CBD) (Convention on Biological Diversity 2010, Barry et al. 2013), and contributes to the Sustaining Arctic Observing Networks (SAON). In relation to the Arctic Council, the CBMP is an important tool for CAFF to implement several of the 17 recommendations from the *Arctic Biodiversity Assessment Report for Policy Makers* (CAFF 2013). In addition, the CBMP is the official Arctic Biodiversity Observation Network (Arctic BON) of the Group on Earth Observations – Biodiversity Observation Network (GEO BON) and a partner to the Global Biodiversity Indicators Partnership (BIP). In relation to GEO BON, the Freshwater CBMP aligns very closely with the approach taken by GEO BON's global Freshwater Biodiversity Observation Network (FW BON) that working to implement common standards and methodologies around the world for in-situ and remotely-sensed observation of freshwater biodiversity. As well, the Focal Ecosystem Component approach used by the CBMP can be relatively easily translated into the Essential Biodiversity Variable concept of GEO BON (Pereira et al. 2013). Countries that are subject to the Water Framework Directive (WFD) of the European Union (EU) (i.e., Finland, Iceland, Norway, Sweden) can also promote synergies between their CBMP activities and WFD outputs to improve the protection of Arctic inland surface waters.

SAFBR outputs will contribute to the above mentioned partnerships and/or national obligations —for example, by helping to measure progress towards the CBD Aichi Biodiversity Targets and measuring the Arctic's progress towards the soon to be released post-2020 Biodiversity Targets —and will gather relevant and reliable information that can inform regional and global processes that affect Arctic biodiversity.

2.4. The State of Arctic Freshwater Biodiversity Report (SAFBR)

2.4.1. Objectives and Overview of Report

The overall goal of the SAFBR was to assess the current status and trends of freshwater biodiversity of FECs both within geographical regions and across the circumpolar Arctic. Specific objectives were to:

- Assess alpha and beta biodiversity and evaluate species distributions and community composition across the Arctic;
- Appraise whether alpha and beta diversity are stable, increasing or decreasing, and if the distribution of particular species is changing;
- Identify geographical locations with high biodiversity (i.e., biodiversity hotspots);
- Determine the primary environmental and human stressors associated with the observed patterns in biodiversity; and
- Identify key monitoring locations for inclusion in future circumpolar assessments of freshwater biodiversity.

2.4.2. Collection and harmonization of data

Metadata collection was undertaken to identify high-quality sources for data collection in the Arctic region. Well-established national monitoring networks and databases in some countries facilitated the collection of contemporary data from a small number of sources, but a lack of coordinated monitoring in other countries required more extensive searches. To ensure broad spatial coverage for the assessment in those countries that lacked national databases (e.g., USA, Canada, Greenland), data were acquired by identifying potential sources, including government-funded monitoring programs, industry-funded monitoring programs, peer-reviewed published literature, and the grey literature, and extracting published data or requesting data access where necessary. Data collection was not exhaustive (for example, it was not possible to obtain data from some sources in Canada), but was as extensive as possible given time constraints. Additionally, Russian involvement in the data collection process was delayed until 2016, significantly limiting the amount of data that could be collected for this effort. Data for lakes and rivers of all sizes were collected for a variety of FECs for the contemporary period (1950 to present), and where possible, for the post-industrial period (1900 to 1950) and pre-1900 (paleo data). Spatial and temporal coverage of data was patchy for many regions, and historical data were lacking for many biotic FECs; however, the initial data collection and assessment can serve to inform the expansion of monitoring to fill identified gaps.

Data were compiled by each country using a standardized format, then reviewed and revised as needed to ensure compliance with data formatting requirements for a single circumpolar database on freshwater biodiversity and supporting variables. Once data from all countries were compiled, reviewed for quality assurance, and entered into the database, harmonization procedures were completed to ensure comparability of data from a variety of data sources. In particular, a nomenclature table was created for each FEC (fish, benthic invertebrates, zooplankton, macrophytes, diatoms, and phytoplankton) to correct and update the taxonomic identifications from the raw data and ensure standardization of taxonomic nomenclature across data originating from a variety of sources. Nomenclature tables updated outdated naming conventions, corrected misspellings or regionally inconsistent spellings, and in some cases were used to create taxonomic complexes where it was necessary to group ambiguous or higher-order identification of individuals.

For each sample in the database, sampling method and equipment details were recorded and compared prior to selection of data for analysis. To reduce variability in the data due to differing methodologies, subsets of data were selected for analysis based on compatibility of equipment (e.g., selecting samples with similar mesh size), collection methods (e.g., grouping methods that would be expected to sample similar portions of the assemblage), sampled habitats (e.g., separation of littoral and profundal samples), and approaches (e.g., samples targeting individual species versus those that collect the full assemblage). Data included a number of measurement types (e.g., presence/absence, counts, densities, biomass). All data were converted to presence/absence to allow broad-scale comparison of data that was inclusive of the greatest number of samples (e.g., including both quantitative and qualitative data), but subsets of quantitative data were also retained for analysis where appropriate. See section 4.1.1.3 for more details on FEC-specific data processing.

Available remote sensing and geospatial data were also collected for the circumpolar region, but largely represented supporting variables (e.g., abiotic variables). Though the use of remote sensing data can support assessment of biodiversity at global scales in terrestrial systems, for example (Turner et al. 2003, Pettorelli et al. 2014), the application of such data in freshwaters is generally limited to description of environmental drivers or Chlorophyll a biomass. Current technology does not support the evaluation of biodiversity of freshwater benthos, plankton, or fish through remote sensing, and data collection was necessarily limited to variables that could describe potential environmental drivers of biodiversity patterns.

The final circumpolar freshwater database is one of the main deliverables of CBMP-Freshwater to CAFF as it documents the data underlying the 2018 SAFBR. This database includes original data, nomenclature tables, and final harmonized data, and will be incorporated into the Arctic Biodiversity Data Service (ABDS). The ABDS is an online, interoperable data management system that serves as a focal point and common platform for all CAFF programs and projects as well as a dynamic source for up-to-date circumpolar Arctic biodiversity information and emerging trends. Incorporation in the ABDS will secure the freshwater database for future assessments and allow the database to be expanded over time as more data are collected or located. This will facilitate future assessments of change in freshwater biodiversity across the circumpolar region.