COMPENDIUM OF RESEARCH

2017/22

Sentinel North

UNIVERSITÉ LAVAL

This document should be cited as:
Sentinel North. (2023). Compendium of research 2017-2022. Environment, Health, Innovation. Gallais, S., Ropars, P., and Lévesque, K. (Eds). Sentinel North, Université Laval, Quebec City, Quebec, Canada.

Editorial team: Sophie Gallais, Pascale Ropars and Keith Lévesque

Produced and published by: Sentinel North, Université Laval

ISBN 978-1-7380285-5-9 (PDF)

URL: hdl.handle.net/20.500.11794/123703

Layout: Duplain Integrated Communication
Translation: ITC traduction
Photographers credits index: Isabelle Dubois/ArcticNet 5
Martin Fortier/ArcticNet 7

Sentinel North is made possible thanks to significant funding from the Canada First Research Excellence Fund.

The program is also partially supported by the Fonds de recherche du Québec

Canada

CANADA FIRST RESEARCH EXCELLENCE FUND | APOGÉE CANADA FONDS D'EXCELLENCE EN RECHERCHE

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Sentinel North

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About this Compendium

In the context of accelerating climate change and socioeconomic development in the Arctic and Subarctic, the Sentinel North research program at Université Laval helps to generate the knowledge needed to improve our understanding of the changing northern environment and its impact on humans and their health. The program fosters the convergence of expertise in the engineering, natural, social and health sciences to catalyze scientific discovery and technological innovation in support of sustainable health and development in the North.

This compendium presents a selection of results from the Sentinel North research program, from its beginning in 2017 through to the end of its first phase in 2022. The results are highlights from innovative research projects and original peer-reviewed publications, and have been integrated into five interdisciplinary chapters addressing major northern issues. Notwithstanding the scale and complexity of these issues, each chapter of the compendium aims to provide new insights through the process of knowledge integration, and fill fundamental gaps in our understanding of the changing North. The five chapters of the compendium each start with an introduction that establishes the significance of the northern issues addressed and the context in which the subsequent Sentinel North results are presented. The selected results can be consulted individually, but have been curated and organized to highlight potential paths of interconnectedness between them as well as to facilitate chapter navigation.

The compendium brings together a wide range of findings from various research teams at Université Laval, who work with their partners in northern organisations and in the public and private sectors. It can serve as a reference for informed decision-making, as a catalyst for further research, as a gateway to a wealth of research data, or as a source of insight for tackling complex problems through innovative, interdisciplinary approaches. Finally, this compendium is not intended to be a comprehensive review of all Sentinel North funded research and outputs. To consult all of the program's publications and results, readers are invited to visit Sentinel North's website.

CHAPTER 1

Marine Environments and Human Health

Changing Arctic and Subarctic Marine Environments and Implications for Human Health

Introduction

Arctic and Subarctic marine environments are experiencing rapid and significant changes associated with climate warming. As a result of this warming, the extent of the Arctic sea ice in summer—an important indicator of change—has decreased by about 40% and its thickness by 65% since 1979 (Roebeling et al., 2021; Lindsay and Schweiger, 2015). The loss of sea ice has important ramifications for physical, chemical and biological processes, including changes to heat flux, general circulation, stratification, nutrient supply, primary production, and energy dynamics of food webs (Carmack et al. 2015; Kortsch et al., 2015; Castellani, 2022).

Ice-free warmer waters and consequent changes in ocean currents have been shown to drive the northward expansion of boreal species, including phyto- and zooplankton, and fish (Fossheim et al., 2015; Lefort et al., 2020; Møller and Nielsen, 2020; Oziel et al., 2020). The drastic retreat of sea-ice cover has also been linked to a longer phytoplankton growing season and a 30% increase in annual net primary production in open waters over the entire Arctic Ocean (Arrigo et al., 2015).

Autotrophic single-celled algae, which are the major primary producers in marine ecosystems, use solar radiation to synthesize essential biomolecules that are eventually incorporated into new biomass at higher trophic levels. In the Arctic, most of the biomolecules synthetized by ice-algae and phytoplankton, is channelled up the food chain through the herbivorous copepod *Calanus spp.* (Falk-Petersen et al., 2007). These lipid-rich copepods are then preyed upon by Arctic cod, *Boreogadus saida*, the staple of piscivorous seals, as well as by beluga and narwhal whales (Welch et al., 1992). A fraction of this primary production

also sinks to the sea floor and provides energy and essential fatty acids to fuel benthic secondary production (Grebmeier and Barry, 1991). The availability and nutritional quality of essential biomolecules at the base of the food web are thus important determinants of the productivity and health of entire marine ecosystems and can be significantly affected by changes in sea ice and the amount of light entering the upper ocean (Søreide et al., 2010). One of the challenges of understanding the dynamics of ice-associated marine food webs under different sea ice regimes, is our ability to adequately quantify the transmission of solar radiation through sea ice (Veyssière et al., 2022; Katlein et al., 2021; Perron et al., 2021).

Climate-related changes in marine food webs can lead to cascading effects on northern coastal communities that rely on country foods of high nutritional quality (Falardeau et al., 2022). Shellfish, fish, seals and whales are central to Inuit culture and constitute a diet rich in essential compounds with known health benefits (Lemire et al., 2015; Rosol et al., 2016; Rapinski et al., 2018; Hibbeln et al., 2006; Hu et al., 2018). It has been suggested that Arctic char (*Salvelinus alpinus*), a key fish species harvested by Inuit and a source of essential fatty acids, could be affected by the northward expansion of boreal species through novel interactions occurring in both bottom-up (e.g., through prey availability and quality) and top-down (e.g., through competition and predation) interactions (Power et al., 2012; Falardeau et al., 2022). Contaminant dynamics—i.e., the bioavailability, uptake, bioaccumulation, and fate of environmental contaminants—can also be affected by changes in food web dynamics, including through the increase in transient-boreal species (McKinney et al., 2012; Lemire et al., 2015; Alava et al., 2017).

Mercury (Hg), methylmercury (MeHg), persistent organic pollutants (POPs) and emerging contaminants of concern like perfluoroalkyl acids (PFAAs), which are transported to the Arctic through long-range atmospheric and oceanic transport (Burkow and Kallenborn, 2000), can be highly detrimental to human health. For instance, Inuit coastal populations have the highest MeHg exposure globally (Basu et al., 2018), with potential deleterious effects on their respiratory, endocrine and central nervous systems (Foster et al., 2012). An understanding of the effects of climate change on contaminant processes and exposure in Arctic and Subarctic marine ecosystems, and how such contaminants affect services and health in northern coastal communities, is needed to inform new policies and improve health outcomes (Achouba et al., 2019; de Moraes Pontual et al., 2021).

This chapter gathers a selection of research results from the Sentinel North program that contribute to improving our understanding of the impacts of environmental changes on key processes in Arctic and Subarctic marine ecosystems and the implications for the health of northern coastal populations. Combined, these results address interdisciplinary and ecosystem-level research questions that pertain to climate-related changes in primary production and food web dynamics, notably the availability and quality of essentials compounds; the trophic flux of energy through the major biota of Arctic and Subarctic marine ecosystems; and the role of marine country foods in contaminants exposure and human health.

KEYWORDS:

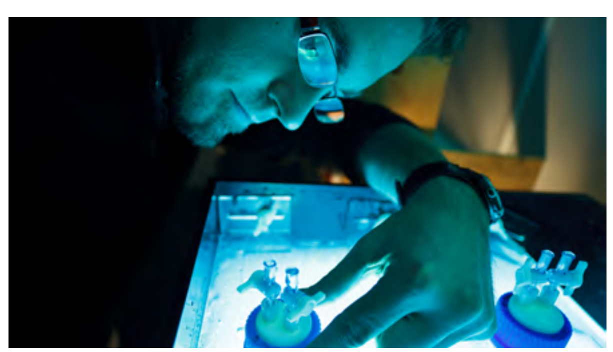
Marine ecosystems, Sea ice, Climate change, Marine food web, Country foods, Oceans, Human health, Energy transfer, Contaminants

1. Shedding Light on Phytoplankton Adaptation to Extreme Conditions

Selected research highlights

Anticipating the Arctic Ocean's responses to shrinking sea-ice and increasing light requires a better understanding of how Arctic phytoplankton adapt to extreme seasonal light regimes.

1.1 Continuous observations over two annual cycles in Baffin Bay, Canada, have shown that net phytoplankton growth can occur in mid-winter and under 100% ice cover. Part of this growth resulted from photosynthesis and highlights the adaptation of Arctic phytoplankton to extreme low-light conditions, which may be key to their survival during the polar night (Randelhoff et al., 2020).

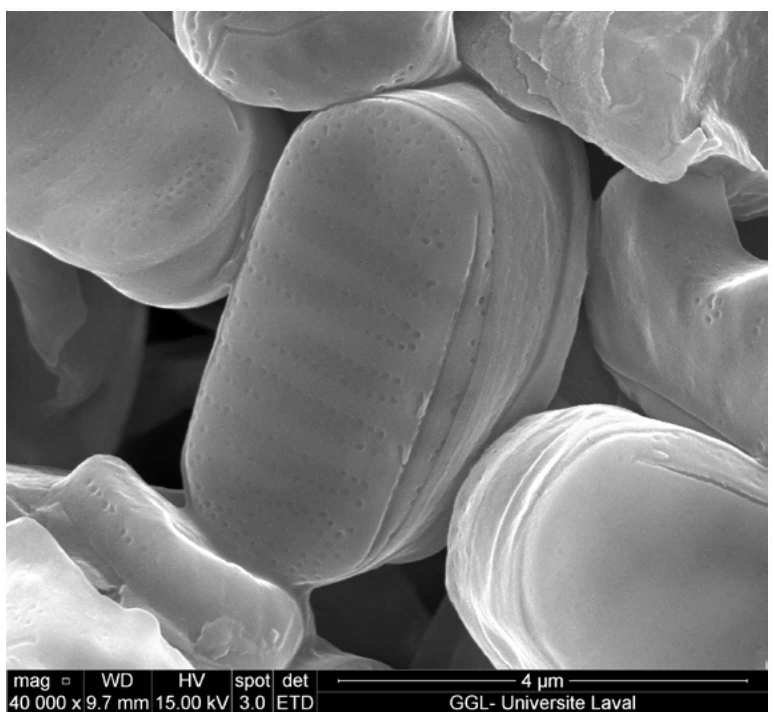


1.2 To improve our understanding of the Arctic Ocean during the polar night, a research team has developed an ultra-sensitive optical sensor in partnership with Biospherical Inc. (Figure 1.2). The sensor, mounted on an autonomous underwater vehicle with enhanced under-ice navigation capabilities, has allowed to make some of the first-ever measurements of light under the ice in the Arctic (Leymarie et al., personal communication).

Figure 1.2
Sensor developed with Biospherical Inc.

1.3 Species-specific photoadaptation strategies, or molecular toolkits, evolved by Arctic diatoms to optimize growth have been shown to be strongly dependent on seasonal light niches (Figure 1.3; Croteau et al., 2022). Unusual photoprotective nonphotochemical quenching and xanthophyll cycle dark patterns could be Arctic diatoms' response to an extreme climate, where light availability is governed by sea-ice cycles, photoperiod, and solar angle (Croteau et al., 2021).

1.4 A first genome-scale model of the species *Fragilariopsis cylindrus*, a pennate sea-ice diatom, was developed to gain insights into the metabolic mechanisms underlying the evolutionary success of diatoms in polar ecosystems. Results demonstrated that the metabolic molecular network in *F. cylindrus* is highly robust in the face of cellular perturbations, a feature that likely helps to maintain cell homeostasis under extreme conditions (Lavoie et al., 2020).



Fragilariopsis cylindrus

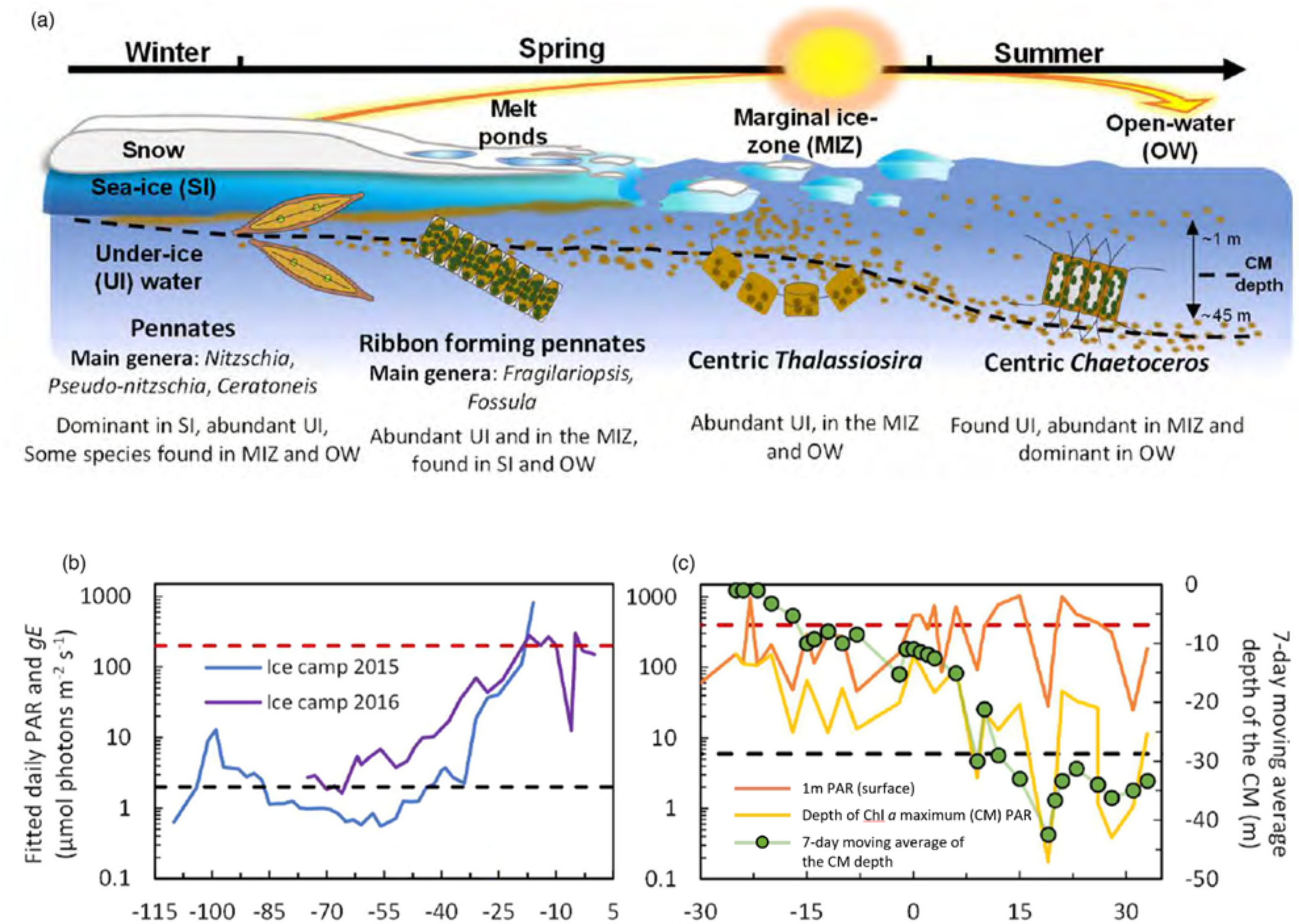


Figure 1.3
Changes in the growing light optima of diatom species favor their succession during the spring bloom in the Arctic. Dotted horizontal lines represent the minimum (black) or maximum (red) growth light intensity (gE) used for the growth of a sympagic (b) or planktonic (c) diatom species. Figure adapted from Croteau et al., 2022, licensed under CC BY 4.0.

"A detailed understanding of how sunlight is reflected and transmitted by the sea ice cover is needed for an accurate representation of critical processes in climate and ecosystem models, such as the ice–albedo feedback."

Katlein et al., 2021

2. Light Transmission Through Arctic Sea Ice

Selected research highlights

As the Arctic warms, sea ice properties are changing, affecting how sunlight is reflected and transmitted to the under-ice water column with associated impacts on primary production and ecosystem dynamics.

2.1 An innovative optical probe has been designed and tested to measure the inherent optical properties of sea ice in situ (Perron et al., 2021). This probe provides a new, fast, and reliable tool to measure light scattering and better predict ice-associated primary production.

2.2 A new multispectral light sensor chain instrument has been developed to enable direct, autonomous and vertically resolved measurements of light attenuation in sea ice. With frequent deployments over a large area, this low-cost instrument could collect ice-associated light data on much larger spatial and temporal scales. Such data will likely improve radiative transfer schemes in large-scale models (Katlein et al., 2021).

3. Determinants of the Nutritional Quality of Primary Producers

Selected research highlights

The quantity and type of lipids, essential fatty acids and antioxidant carotenoid pigments synthesized by ice algae and phytoplankton are crucial for the health and function of the Arctic marine food web and will be affected, either directly or indirectly, by the rapid transformation of the Arctic environment.

3.1 Changes in the marine physicochemical environment (e.g., seawater temperature, salinity, pH, nutrients and light) along a 3,000 km transect indirectly affected the essential fatty acid, including the omega-3 composition, and carotenoid pigments composition of marine phytoplankton through shifts in species assemblages following spring sea-ice retreat and successive blooms (Marmillot et al., 2020; Amiraux et al., 2022).

3.2 As part of a comparative study of Nunavik marine environments, pH was positively correlated with the production of eicosapentaenoic acid (EPA), one of the key long-chain omega-3 fatty acids, in diatoms. Results obtained through additional covariance analyses suggest a direct and detrimental effect of low pH on diatom cell physiology (Cameron-Bergeron, 2020). Some of the fastest rates of ocean acidification around the world have been observed in the Arctic Ocean and this could have significant effects on the production and transfer of essentials compounds up the food chain.

4. A Changing Marine Environment and Shifts in Species Distribution

Selected research highlights

In the Arctic and Subarctic marine environment, climate warming is triggering poleward shifts in species distributions, which in turn can cause community-wide reorganizations and changes in food web dynamics.

4.1 The significant increase in North Atlantic current surface velocities through the European Arctic Corridor over the last 24 years has led to the poleward expansion of *Emiliania huxleyi*, a phytoplankton tracer of temperate ecosystems (Figure 4.1). This physical and biological "Atlantification"of the Arctic Ocean could affect the entire marine ecosystem by shifting species distributions and impacting energy transfer to higher trophic levels (Oziel et al., 2020).

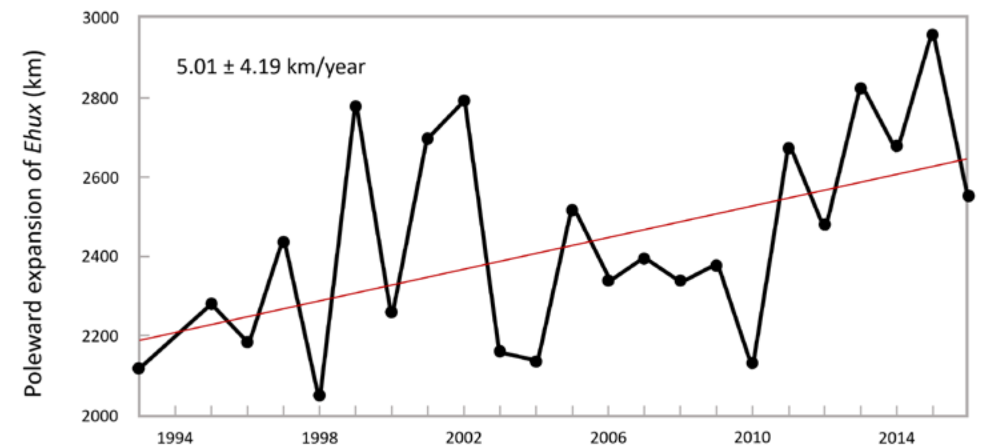
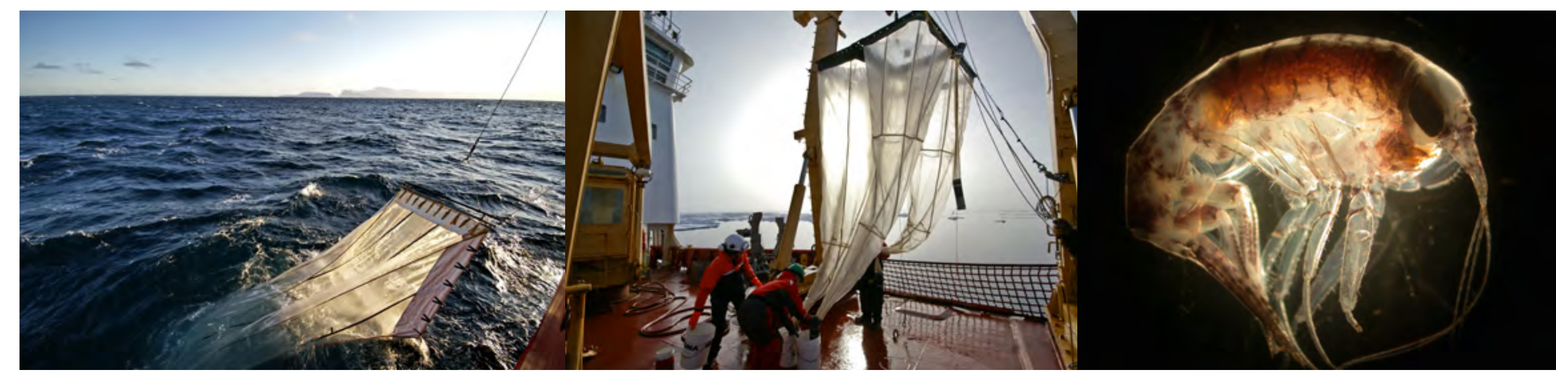


Figure 4.1
Moving north of *Emiliania huxleyi* (Ehux). Figure taken from Oziel et al., 2020, licensed under CC BY 4.0.



4.2 A morphological trait-based analysis of over 28,000 zooplankton images collected in Baffin Bay, Canada, with an underwater imaging system, revealed that the distribution of copepod traits varies according to water mass properties and spatio-temporal dynamics of ice melt. Large-bodied copepods such as *Calanus hyperboreus* are more abundant in ice-covered Arctic waters whereas smaller species like *Calanus finmarchicus* dominate the open waters advected from the Atlantic (Vilgrain et al., 2021).

Illustration of Arctic copepods.
© Laure Vilgrain

4.3 Plankton imaging systems are proving key to gain insight into the ecology of secondary producers. In particular, these systems can now be coupled with machine learning techniques to track the distribution of zooplankton using morphological functional trait expression at the individual-level (Orenstein et al., 2022). This novel approach will help shed new light on food web dynamics and carbon cycling in the oceans.

5. Trophic Relationships and Energy Transfer up the Food Web

Selected research highlights

Identifying trophic relationships and the regional and seasonal variability of the dominant pathways by which energy and carbon move through Arctic and Subarctic food webs is essential to determining ecosystem stability, complexity and resilience to climate-induced changes.

5.1 Using fatty-acid markers of diatoms, it was demonstrated that the essential fatty acid content of copepods is influenced primarily by recent feeding on the subsurface chlorophyll maxima (SCM) (Figure 5.1). Long-lived SCMs remain key for zooplankton and the trophic transfer of essential fatty acids in Arctic Ocean food webs. These results also challenge the paradigm that copepods must rely primarily on short-term surface blooms to rapidly store lipids for the following winter (Marmillot, 2023).

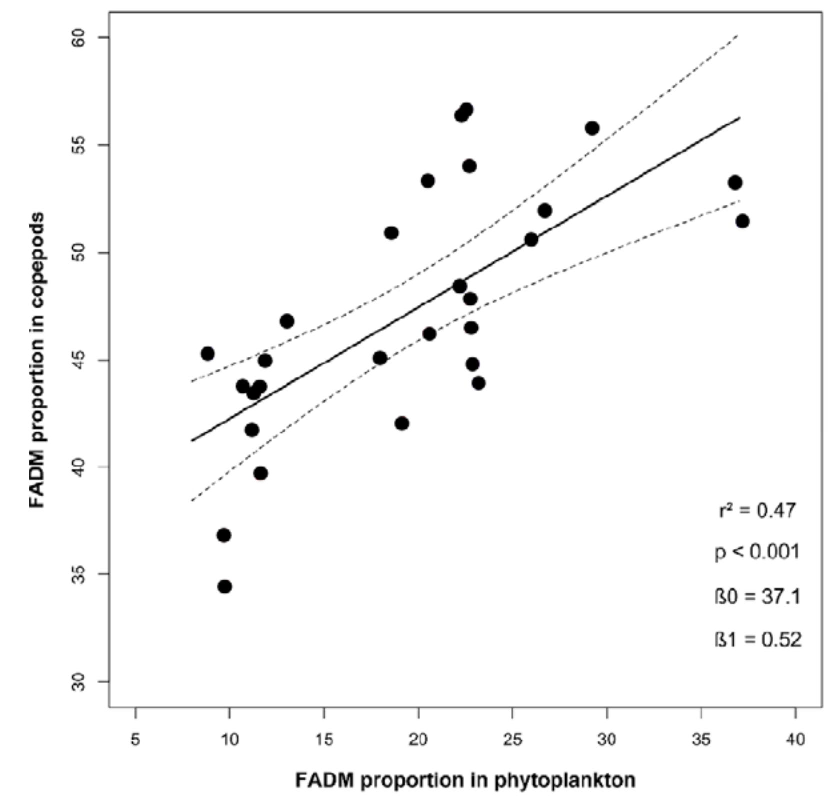


Figure 5.1
Relationship between diatom fatty acid markers (FADM) of phytoplankton and copepods. The dotted lines represent the 95% confidence interval. Figure adapted from Marmillot, 2023, © Vincent Marmillot.

5.2 Strong correlations were observed between the seasonal and annual ice-associated algal production of highly branched isoprenoids and essential polyunsaturated fatty acids (e.g., omega-3) and their presence in Greenland cockle (*Serripes groenlandicus*), an Arctic filter-feeding bivalve (Amiraux et al., 2021). These results underscore the influence of sea-ice lipid production on the quality and reproductive capacity of bivalves and highlight the crucial role that pelagic-benthic coupling plays in nutrient cycling and energy transfer in Arctic food webs.

Serripes groenlandicus

5.3 In Nunavik, benthic organisms with various feeding strategies exhibited differences in nutritional value. Species in higher trophic levels, such as the sea star, generally had higher fatty acid concentrations than those at lower trophic levels (Figure 5.3). They also exhibited levels of selenium comparable to other healthy country foods such as seal and beluga meat and blubber (Van Doorn, 2021).

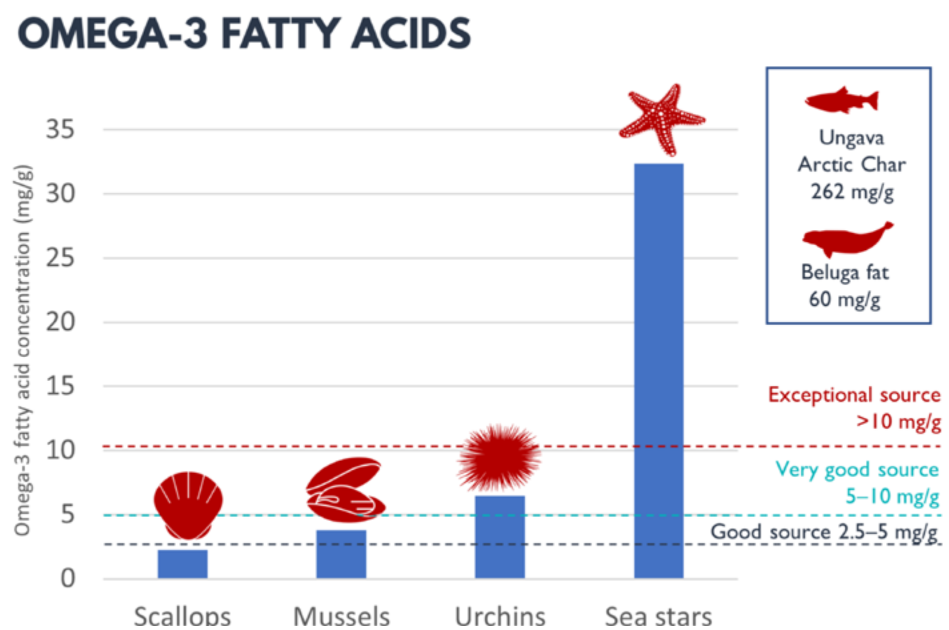


Figure 5.3
Starfish are exceptional sources of omega-3. © Littoral Chair

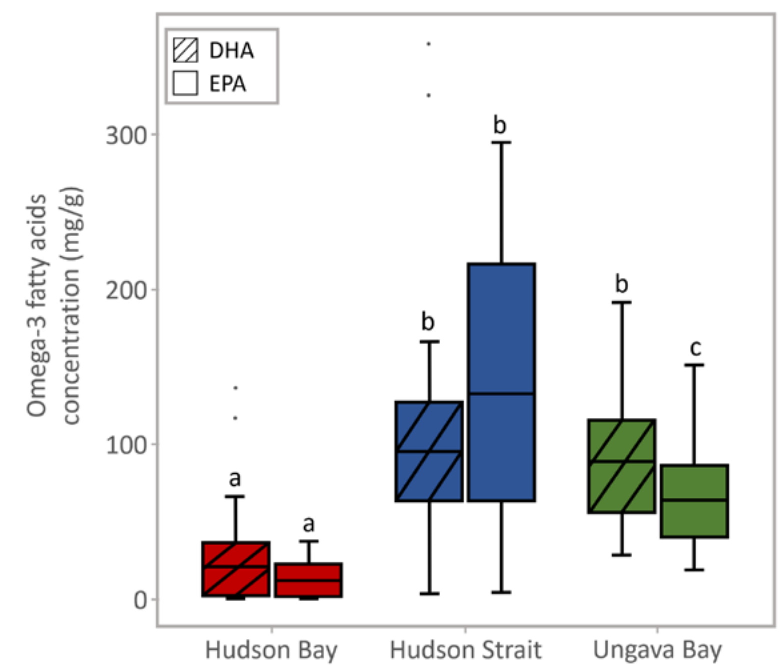


Figure 5.4
Omega-3 content of Arctic char from the three marine regions of Nunavik. The boxplots represent the arithmetic means of the omega-3 concentrations and the standard error of the means. © Sara Bolduc

5.4 The nutritional value of Arctic char (*Salvelinus alpinus*), as measured by concentrations of long-chain polyunsaturated omega-3 in the flesh, varies by region (Figure 5.4) and is linked to differences in diet. Arctic char populations from Hudson Bay and Hudson Strait have a more pelagic diet, while those from Ungava Bay feed on benthic prey. In all three regions of Nunavik, Arctic char have exceptional concentrations of omega-3 (Bolduc, 2021).

Arctic char population genomics

Arctic char is a key species for northern coastal communities, representing a traditional food source rich in essential compounds. The population structure of Arctic char in Nunavik was investigated using genomic methods. The results showed that Arctic char populations are adapted to their environment (temperature, salinity, etc.) and genetically distinct between the three ecological regions of Nunavik: Hudson Bay, Hudson Strait, and Ungava Bay. These results can contribute to regional sustainable management plans for Arctic char fisheries (Dallaire et al., 2021).

6. Environmental Contaminants and Human Health Implications in the North

Selected research highlights

Exposure of northern coastal communities to environmental contaminants through a traditional diet remains a major concern to human health in the Arctic. Monitoring studies provide essential information for local organizations to manage human health risks from exposure to contaminants, while promoting local country foods, which are a source of exceptional nutritional quality and of cultural, social, and economic importance to communities.

6.1 The estimated mean methylmercury (MeHg) intakes based on total country food consumption among pregnant Inuit women in Nunavik revealed significant monthly variations (Figure 6.1) and were two-fold greater than the recommended guidance values for pregnant women. Beluga meat was the primary source of daily MeHg intake for these women, especially during summer and early fall. Understanding seasonal variations in country food consumption is critical to adequately assess MeHg exposure, adopt timely preventive interventions and evaluate the effectiveness of international regulations (de Moraes Pontual et al., 2021).

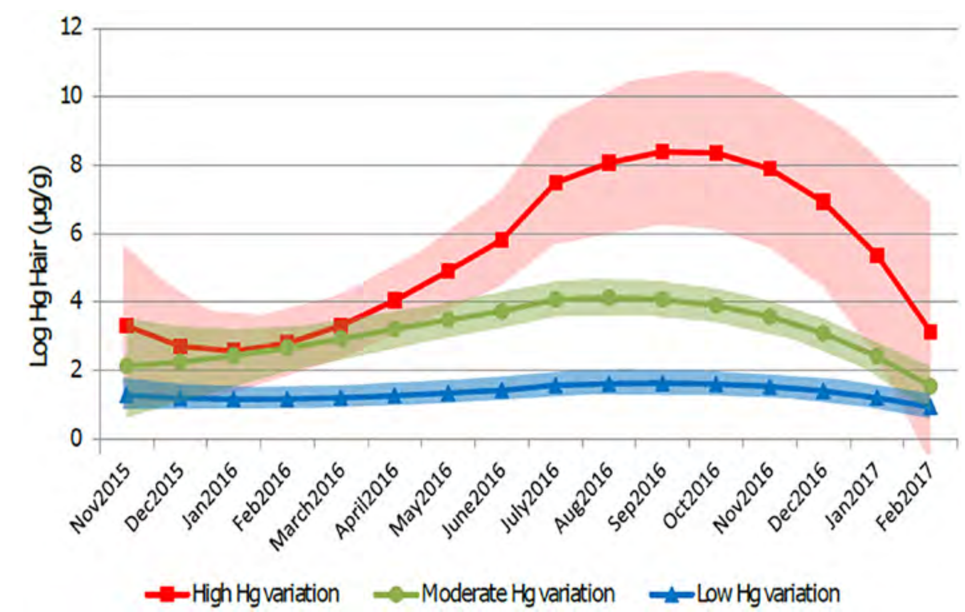


Figure 6.1
Monthly change in concentration of mercury in the hair of three groups of pregnant women in Nunavik. Shaded areas represent the 95% confidence interval. Figure taken from de Moraes Pontual et al., 2021, licensed under CC BY-NC-ND 4.0.

6.2 Selenoneine is the major selenium species in beluga mattaaq. It was also found in high concentrations in the red blood cells of the Inuit in Nunavik (Figure 6.2) and was positively correlated to their consumption of this highly praised country food. One hypothesis under investigation is that selenoneine may protect from methylmecury toxicity by increasing its demethylation in red blood cells (Achouba et al., 2019; Little et al., 2019).

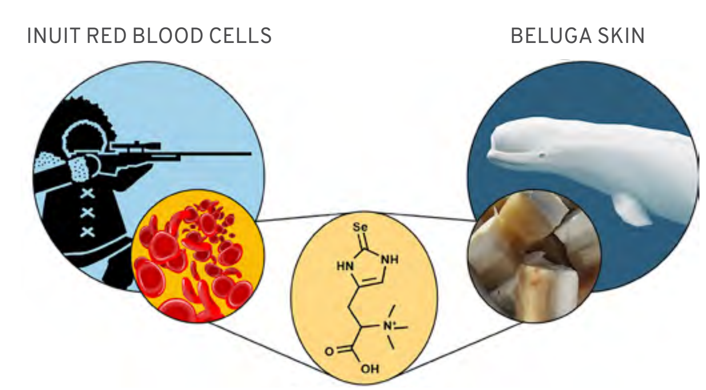


Figure 6.2
Selenoneine is found in high concentrations in Inuit red blood cells and beluga mattaaq. Figure taken from Achouba et al., 2019, licensed under CC BY-NC-ND 4.0.

Towards a portable tool to measure contaminants in country foods

Major steps have been taken to develop a reliable and effective portable tool for detecting mercury in country foods. A new mercury-sensitive fluorophore was synthesized (Picard-Lafond et al., 2020) and its detection properties were investigated. Metal-enhanced fluorescence (MEF) was used in the design of the mercury-sensitive sensor to improve the brightness and photostability of target-responsive fluorophores (Picard-Lafond et al., 2022). MEF has excellent potential for heavy metal detection by fluorescence.

6.3 Long-chain perfluoroalkyl acids (PFAAs) are highly persistent synthetic compounds that can migrate to the poles and accumulate in marine species, particularly those at the top of the food chain. PFAAs exposure concentrations in the Inuit population of Nunavik were shown to be up to seven times higher than those of the general Canadian population (Aker et al., 2021). A host of health effects have been associated with elevated PFAAs exposure in other populations.

6.4 The exposure of pregnant Inuit women in Nunavik to long-chain perfluoroalkyl acids (PFAAs) congeners, such as PFNA, PFDA, and PFUdA, has increased between 2011 and 2017 by as much as 21% in some cases. These exposure levels are among the highest reported in the circumpolar Arctic and elsewhere and indicate that pregnant women in Nunavik are disproportionately exposed to these PFAAs (Figure 6.4) through their bioaccumulation in marine country foods. The implementation of strict regulations in regard to PFAAs is urgently needed to protect traditional country foods (Caron-Beaudoin et al., 2020).

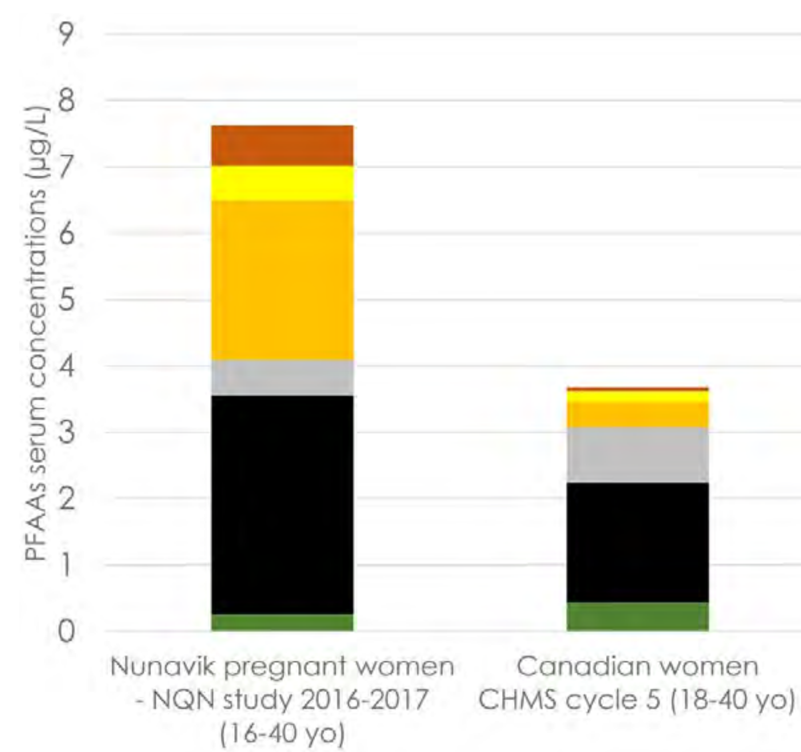


Figure 6.4
The concentration of perfluoroalkyl acids (PFAAs) is higher in pregnant women in Nunavik than in the average Canadian pregnant woman. Figure taken from Caron-Beaudoin et al., 2020, licensed under CC BY-NC-ND 4.0.

From Research Results to Policy Action

Results obtained through a partnership between Sentinel North researchers at Université Laval and Inuit of Nunavik are proving key for Canada's proposal to the Stockholm Convention to regulate per- and polyfluoroalkyl substances (PFAS) and their precursors, also known as 'forever chemicals'. At the 2022 meetings of the Persistent Organic Pollutants Review Committee, Canada's proposal noting the environmental injustice faced by Inuit led the Committee to accept the assessment that these chemicals pose a significant risk to the environment and human health. Long chain-PFAAs therefore moved to the next step in the process, which is to assess the socio-economic impacts of regulatory and management options. Following this step, the Conference of the Parties will decide, in a precautionary manner, whether to ban the use of, or impose strict regulatory measures on, these chemicals.

PFAS are used in many consumer products

Effectively addressing the effects of climate change and environmental contaminants to improve health outcomes requires transdisciplinary perspectives and greater integration of the knowledge production process into policymaking.

Research Projects Cited in this Chapter

The knowledge and technological advances referenced in this chapter were generated by several Sentinel North interdisciplinary research teams. These scientific contributions were gathered from the projects listed below, which involved, in addition to the principal investigators, numerous researchers, graduate students, postdoctoral fellows, research professionals, collaborators, partners from northern organizations and national and international partners from the public and private sectors.

- A better understanding of light-matter interaction: Bridging the gap between micro and macro scales, and developing new devices and approaches for the North

  Principal Investigator: Pierre Marquet (Dept. of Psychiatry and Neurosciences)

- BRIGHT: Bridging global change, Inuit health and the transforming Arctic Ocean

  Principal Investigators: Mélanie Lemire (Dept. of Social and Preventive Medicine), Jean-Éric Tremblay (Dept. of Biology)

- Deciphering host-microbial interactions for cardiometabolic and mental health disorders with novel multimodal light-based sensing tools

  Principal Investigators: Denis Boudreau (Dept. of Chemistry), André Marette (Dept. of Medicine)

- Enabling tools for the monitoring of food quality in the northern environment

  Principal Investigators: Dominic Larivière (Dept. of Chemistry), Jean Ruel (Dept. of Mechanical Engineering)

- The use of diatom microalgae for improving the treatment of the light-driven dysfunctions of the biological clock in Arctic human populations

  Principal Investigator: Johann Lavaud (Dept. of Biology)

- Sentinel North partnership research chair on ecosystemic approaches to health

  Chairholder: Mélanie Lemire (Dept. of Social and Preventive Medicine)

- Sentinel North research chair on the applications and theory of network analysis

  Chairholder: Antoine Allard (Dept. of Physics, Physical Engineering, and Optics)

Some results presented in this chapter are also drawn from research projects conducted by recipients of Sentinel North Excellence scholarship and postdoctoral fellowship awards.

- Génomique de populations de l'omble chevalier au Nunavik et son adaptation locale aux conditions environnementales

  Xavier Dallaire (Master's Scholarship)

- Impact of climate change on the nutritional quality of traditional Inuit foods: *Mytilus edulis* and *Mya truncata* (Bivalvia)

  Rémi Amiraux (Postdoctoral Fellowship)

- In situ optical measurements in sea ice

  Christian Katlein (Postdoctoral Fellowship)

- Modélisation des réseaux moléculaires de l'horloge biologique des diatomées arctiques aux modèles humains

  Michel Lavoie (Postdoctoral Fellowship)

- Network structures of Northern oceanography

  Achim Randelhoff (Postdoctoral Fellowship)

- The association between per and polyfluoroalkyl substances (PFAS) and metabolic outcomes among Nunavimmiut adults

  Amira Aker (Postdoctoral Fellowship)

Research Projects
in this Chapter

Sentinel North has developed partnerships with leading international institutions to conduct innovative and interdisciplinary research projects. The following joint collaborative projects have contributed to the results of this chapter.

- Artificial intelligence application to the identification of functional traits of zooplankton from high-resolution images (ARTIFACTZ)

  Principal Investigators: Éric Debreuve (Université Côte d'Azur), Frédéric Maps (Dept. of Biology)

- Calanus redness index from artificial intelligence applications to image analysis (CARDINAL)

  Principal Investigators: Sünnje Basedow (UiT The Arctic University of Norway), Frédéric Maps (Dept. of Biology)

- Characterization of underneath sea-ice light field variability in the Arctic ocean using underwater and aerial autonomous vehicles

  Principal Investigators: Marcel Babin (Dept. of Biology), Jørgen Berge (UiT The Arctic University of Norway)

- The role of circadian clocks in seasonal synchrony in the Arctic

  Principal Investigators: Johann Lavaud (Dept. of Biology), David Hazlerigg (UiT The Arctic University of Norway)

- Takuvik Joint International Research Unit

  Director: Marcel Babin (Dept. of Biology)
  National Centre for Scientific Research, France
  Associated with the CERC in Remote Sensing of Canada's New Arctic Frontier

Ongoing Sentinel North Research Projects

Several research projects supported by Sentinel North and through joint funding initiatives are ongoing as part of the second phase of the program (2021-2025). These projects, listed hereunder, continue to fill fundamental gaps in our scientific knowledge of the changing North.

- Artificial intelligence application to the identification of functional traits of zooplankton from high-resolution images (ARTIFACTZ)

  Principal Investigators: Éric Debreuve (Université Côte d'Azur), Frédéric Maps (Dept. of Biology)
  Project jointly funded by Sentinel North and Université Côte d'Azur

- CalAct: The impact of light and temperature on Calanus activity patterns in the Arctic

  Principal Investigators: Marcel Babin (Dept. of Biology), Malin Daase (UiT The Arctic University of Norway)
  Project jointly funded by Sentinel North and UiT The Arctic University of Norway

- Calanus redness index from artificial intelligence applications to image analysis (CARDINAL)

  Principal Investigators: Sünnje Basedow (UiT The Arctic University of Norway), Frédéric Maps (Dept. of Biology)
  Project jointly funded by Sentinel North and UiT The Arctic University of Norway

- Characterization of underneath sea-ice light field variability in the Arctic Ocean using underwater and aerial autonomous vehicles

  Principal Investigators: Marcel Babin (Dept. of Biology), Jørgen Berge (UiT The Arctic University of Norway)
  Project jointly funded by Sentinel North and UiT The Arctic University of Norway

- Last ice microbiomes and Arctic ecosystem health

  Principal Investigators: Alexander Culley (Dept. of Biochemistry, Microbiology and Bio-informatics), Warwick Vincent (Dept. of Biology)

- Linking the marine environment and the nutritional quality of shellfish and beluga near Quaqtaq

  Principal Investigators: Mélanie Lemire (Dept. of Social and Preventive Medicine), Jean-Éric Tremblay (Dept. of Biology)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Nunatsiavut Coastal Interactions Project (NCIP): Climate, Environment and Labrador Inuit subsistence strategies

  Principal Investigator: James Woollett (Dept. of Historical Sciences)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Screening for emerging Arctic health risks to circumpolar human populations (SEARCH)

  Principal Investigators: Pierre Ayotte (Dept. of Social and Preventive Medicine), Torkjel M. Sandanger (UiT The Arctic University of Norway)
  Project jointly funded by Sentinel North and UiT The Arctic University of Norway

- Sustainable and resilient country food systems for future generations of Nunavimmiut – Promoting food security while adapting to changing northern environments

  Principal Investigators: Frédéric Maps (Dept. of Biology), Tiff-Annie Kenny (Dept. of Social and Preventive Medicine)

- The role of circadian clocks in seasonal synchrony in the Arctic

  Principal Investigators: Johann Lavaud (Dept. of Biology), David Hazlerigg (UiT The Arctic University of Norway)
  Project jointly funded by Sentinel North and UiT The Arctic University of Norway

- TININNIMIUTAIT: Assessing the potential of local marine foods accessible from the shore to increase food security and sovereignty in Nunavik

  Principal Investigators: Lucie Beaulieu (Dept. of Food Sciences), Ladd Johnson (Dept. of Biology)

- UVILUQ: The use of liquid biopsies for monitoring the health of coastal marine ecosystems

  Principal Investigator: Yves St-Pierre (Eau Terre Environnement Research Centre, Institut national de la recherche scientifique)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Sentinel North partnership research chair on ecosystemic approaches to health

  Chairholder: Mélanie Lemire (Dept. of Social and Preventive Medicine)

- Sentinel North research chair on the applications and theory of network analysis

  Chairholder: Antoine Allard (Dept. of Physics, Physical Engineering, and Optics)

- Takuvik Joint International Research Unit

  Director: Marcel Babin (Dept. of Biology)

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Acknowledgments
The following research team members contributed to the review of the scientific highlights presented in this chapter:

Philippe Archambault, Marcel Babin, Sarah Bolduc, Denis Boudreau, Marie-Hélène Forget, Christian Katlein, Johann Lavaud, Mélanie Lemire, Frédéric Maps, Jean-Sébastien Moore, Jean-Éric Tremblay.

We also thank Mary Thaler for her comments on the introduction.

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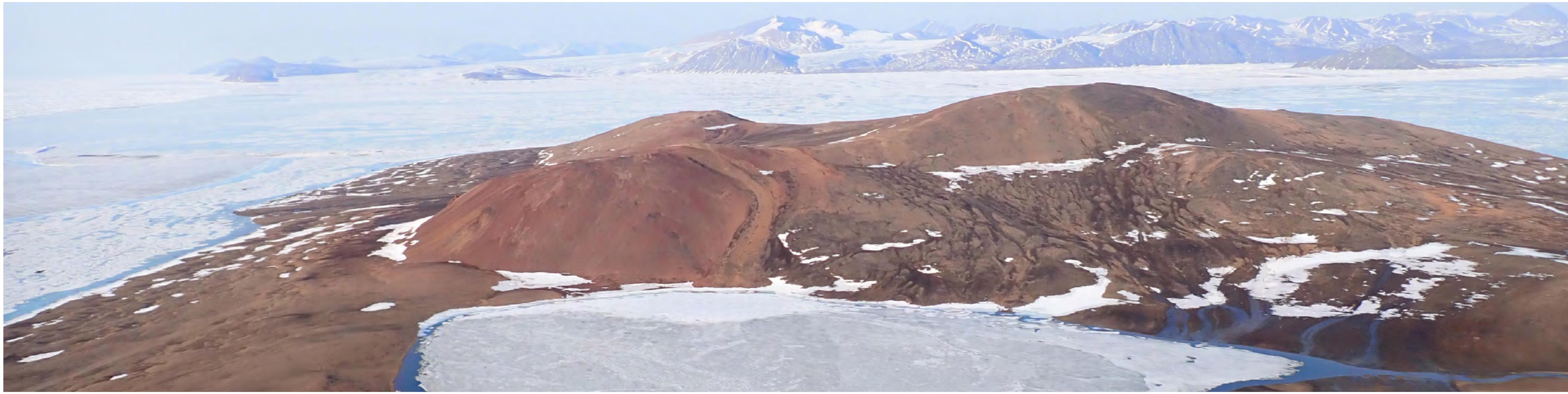
CHAPTER 2

Permafrost Landscapes and Freshwater Systems

Sentinel North



Permafrost Landscapes and Freshwater Systems in a Changing North: Towards an Integrated Understanding

Introduction

Climate-driven changes to the cryosphere are having unprecedented impacts well beyond northern regions (AMAP, 2011; AMAP, 2021). In the Arctic and Subarctic, permafrost, snow and freshwater ice dominate the terrestrial landscape and are host to unique and interconnected habitats and ecosystems. Changes to the cryosphere are impacting these environments directly, while changing the physical, biogeochemical, and biological linkages between them (Vincent et al., 2011). Climate warming is being further exacerbated by the albedo effect associated with diminishing snow and ice (Barry, 2022) as well as the release of greenhouse gases from large quantities of organic carbon stored in northern permafrost (Schuur et al., 2015).

Permafrost, ground that remains at or below 0°C for a minimum of two consecutive years (van Everdingen, 1998), underlies approximately 22% of the Northern Hemisphere (Obu et al., 2019), and over half of Canada's land area (Heginbottom et al., 1995). During the late 20th and early 21st century, rates of permafrost thaw in colder permafrost sites across the Arctic have been higher than at any other time on record (AMAP, 2021; Smith et al., 2022). Northern environments and infrastructure dependent on permafrost stability are facing rapidly increasing effects as the climate warms and development increases (Vincent et al., 2017; Hjort et al., 2022). Thermokarst lakes, formed from thawing permafrost, are a dominant feature across the North (Grosse et al., 2013) and are known sources of significant greenhouse gas emissions to the atmosphere (Matveev et al., 2016; Matveev et al., 2018). The development of new technologies that can be deployed in remote environments to detect and monitor these emissions (Jobin et al., 2022; Paradis et al., 2022) is even more critical in the context of increasing climate feedback effects.

Increasing temperatures and its related impacts are also affecting northern river systems through changes to groundwater flow (Sergeant et al., 2021), altering the properties of the Arctic snowpack, and causing reduction in year-round ice cover of High Arctic lakes. These lakes are responding discontinuously to climate-driven change and can therefore be seen as sentinels for arctic ecosystem health beyond the regional scale (Mueller et al., 2009). Some shallow lakes are no longer freezing to the bottom in winter, leading to an increased period of biological activity, and in turn, increased greenhouse gas production (Mohit et al., 2017). Snow and snow properties vary across northern regions, but a general decrease in snow cover has been documented across the Arctic (Liston and Hiemstra, 2011; AMAP, 2017). In the low Arctic, snow cover is complex, with layers of different densities and a high level of interannual variability, impacting heat flux to the ground and atmosphere (Lackner et al., 2021). Changes to snow conditions and properties are in turn affecting the behaviour, reproduction, and survival of northern wildlife (Berteaux et al., 2016).

The microbiome of cryospheric ecosystems is still little understood, but studies indicate that many northern environments are host to unique microbial communities that may be key to the overall health of ecosystems and humans (Jungblut et al., 2021). The warming climate is threatening the habitats of certain polar microbes (e.g., Tsuji et al., 2019a; Tsuji et al., 2019b; Tsuji et al., 2022), causing cascading effects throughout other microbial communities within connected hydrologic habitats (Comte et al., 2018). The discovery of new and diverse bacterial and viral communities in northern freshwater systems could bring about a better understanding of carbon cycling in northern ecosystems (Vigneron et al., 2019; Vigneron et al., 2020; Labbé et al., 2020).

Efforts to protect and document these unique habitats, before they disappear, are being prioritized through efforts such the cryopreservation of microbiomes and the creation of protected areas like the Tuvaijuittuq Marine Protected Area in the Canadian High Arctic (Vincent and Mueller, 2020).

Understanding and tracking the accelerating transformations in northern landscapes due to climate change is more critical than ever, requiring cross-sectoral research approaches and the development of novel technologies. Sentinel North's interdisciplinary research approach is bringing to light new information about the changing northern environment, and driving innovative developments in the fields of optics, biotechnology and green energy to better understand and address these transformations. This chapter presents Sentinel North's research advances related to the changing Arctic and Subarctic environments and the new tools and methods being developed to track these changes and their impacts on interconnected ecosystems. From thawing permafrost to thermokarst ponds to High Arctic lakes and glaciers and their habitats, Sentinel North is stepping up as a leader in interdisciplinary research to better comprehend Canada's warming northern regions.

KEY WORDS:

Cryosphere, Permafrost, Warming, Thermokarst, Greenhouse Gases, Microbiome, Groundwater, High Arctic Lakes, Optical Detection

1. Permafrost Degradation and its Impact on Landscape and Infrastructure

Selected research highlights

The permafrost is warming and thawing at an accelerating rate. Permafrost thawing induces soil compaction and causes impacts with various ramifications on the different northern landscapes and infrastructure.

1.1 Permafrost thawing contributes to the formation of lakes, but drained lake basins have increased even more rapidly. Therefore, climate warming is causing a net loss of lake area in permafrost regions. These changes in northern landscapes affect hydrology, carbon cycle, plant succession, habitats, subsistence activities, and infrastructure (Jones et al., 2022).

1.2 Over the past 50 years, the ground thermal regime and permafrost reaction to climate warming has varied significantly across the landscape near Kangiqsualujjuaq, Nunavik. This large variability, measured within a small area, highlights the importance of characterizing field conditions properly to accurately predict the influence of climate warming on permafrost (Deslauriers et al., 2021).

1.3 A new hybrid multicore fibre technology was developed that assembles three optical fibers into a microstructured polycarbonate preform. Bragg grating characterization of this glass-polymer hybrid fibre has shown that it is seven times more sensitive than standard multicore optical fibs. This fibre has the potential to be extended over kilometres and has several possible applications, including monitoring permafrost thaw settlement (Boilard et al., 2020).

1.4 Permafrost knowledge must be shared with northern communities to support decisions concerning evidence-based land-use planning and adaptation to climate change. The Permafrost Data platform is a knowledge transfer tool that shares the acquired permafrost data with the northern villages of Nunavik as well as with public decision-makers.

Training the Next Generation of Permafrost Engineers

Permafrost engineering requires specialized knowledge and techniques. To train professionals, graduate students and postdoctoral fellows on these challenges, Sentinel North coordinated the 2019 International PhD School "Permafrost Engineering Applied to Transportation Infrastructure," held on the campus of Aurora College in Inuvik, Northwest Territories. This cutting-edge training provided participants with an understanding of the context and challenges of building and maintaining infrastructure in permafrost environments, and the fundamental knowledge to deal with complex situations in unstable permafrost contexts.

2. Thermokarst Lakes and Carbon Dynamics Associated with Permafrost Degradation

Selected research highlights

Thawing of ice-rich permafrost leads to the formation of thermokarst lakes. These aquatic environments are a significant source of methane (CH_4) and carbon dioxide (CO_2) in the atmosphere. It is essential to deepen our understanding of the microorganisms adapted to these extreme environments and the biogeochemical processes related to greenhouse gas production.

2.1 Thermokarst lakes formed from thawing lithalsa emit CH_4 and CO_2 into the atmosphere upon formation. Results indicate that CO_2 and CH_4 diffusion rates from Nunavik lithalsas are generally higher in areas of increased permafrost degradation (Figure 2.1). These results suggest that thermokarst development in a lithalsa-dominated landscape will be accompanied by increased greenhouse gas emissions for several decades (Matveev et al., 2018).

2.2 Despite the predominance of winter and ice cover for much of the year, most thermokarst lake studies have been conducted in summer. Yet recent results suggest that the summer microbial community represents a transient stage of the annual cycle and that CH_4 and CO_2 continues to be produced under the ice cover by a taxonomically distinct winter community and various permafrost carbon transformation mechanisms (Vigneron et al., 2019).

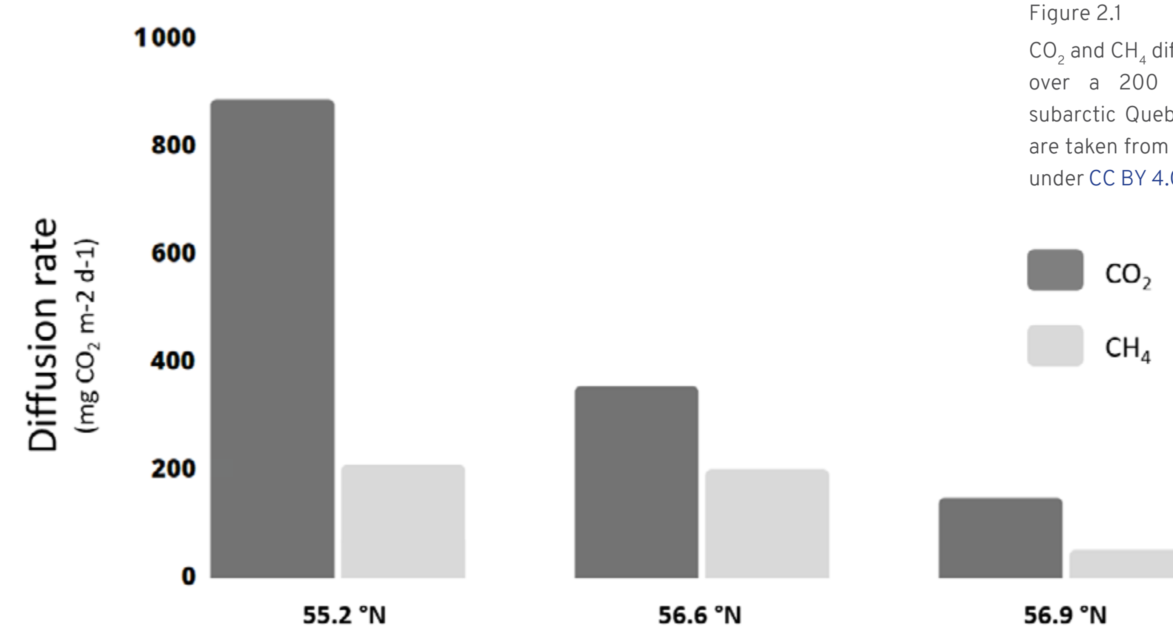


Figure 2.1
CO_2 and CH_4 diffusion rate from lithalsa lakes over a 200 km latitudinal gradient in subarctic Quebec. Data used for this figure are taken from Matveev et al., 2018, licensed under CC BY 4.0.

2.3 Candidate phyla radiation (CPR) are present year-round in thermokarst lakes, raising questions about their role in the biogeochemistry of these lakes. Genomic analysis revealed that these very small microorganisms are potentially very abundant and play a key role in carbon transformation regardless of the season. The importance of CPR has been largely underestimated and overlooked in lake ecosystems (Vigneron et al., 2020).

2.4 In subarctic Quebec, it was shown that organic-rich peatland thermokarst lakes have extremely high CH_4 concentrations in winter under the ice cover, and high emissions into the atmosphere during spring break-up. These results highlight the need to consider large seasonal fluctuations in methane emissions from thermokarst lakes when estimating annual carbon fluxes (Matveev et al., 2019).

2.5 Permafrost thawing leads to increased dissolved organic carbon (DOC) in lake environments (browning). This increase in DOC causes the attenuation of photosynthetically active radiation and ultraviolet radiation in lakes, leading to significant changes in ecosystems. To better understand the phenomenon of lake browning and its consequences, the MyLake model has been improved to consider light attenuation in lakes in response to changes in DOC load (Pilla and Couture, 2021).

3. Detecting On-Site Greenhouse Gas Emissions

Selected research highlights

To better understand carbon flux and greenhouse gas emissions, Sentinel North teams are developing devices to detect and quantify gases in the lower atmosphere.

3.1 Remarkable advances have been made in the design of mid-infrared (2.5–5 micron) laser sources for detecting methane (CH_4), a gas that exhibits strong absorption bands in these wavelengths (Figure 3.1; Jobin et al., 2022). Notably, research has shown that the concentration of a gas can be measured on a microphone using the photo-acoustic effect with a broad spectral band laser source.

3.2 The first all-fibre laser operating in the mid-infrared range in the self-triggered regime using a dysprosium-doped silica fibre as a saturable absorber has been demonstrated. This laser could be robust and reliable enough to be deployed in extreme environments and detect more than one gas, including CH_4, through its broad emission spectrum (Paradis et al., 2022).

3.3 Optical fibers with Ga_2O_3-rich BGG glasses with low losses (< 1 dB m^{-1}) were fabricated for the first time since the discovery of this glass family (Guérineau et al., 2023). The development of optically active and passive fibers from these glasses allows the design of new, more robust and reliable laser systems, while improving methane detection sensitivity.

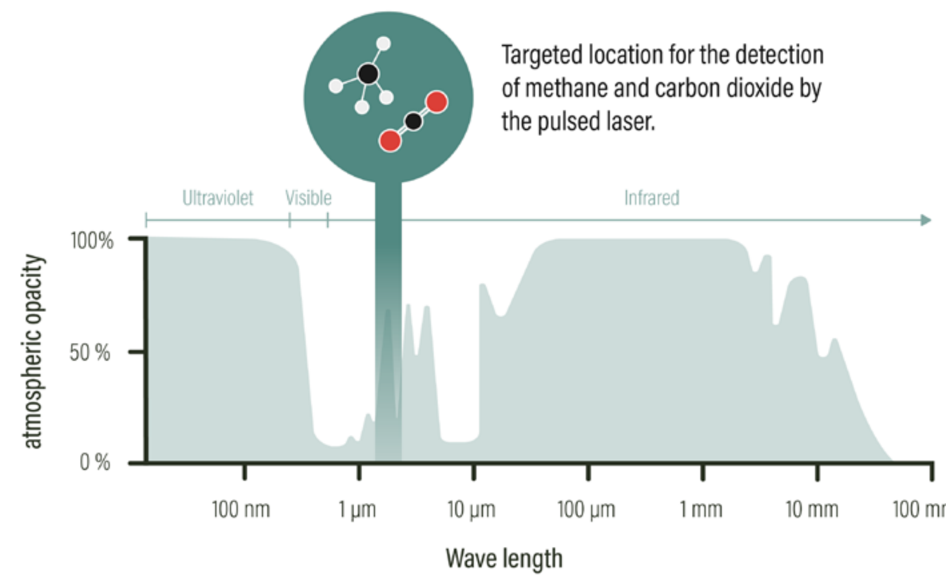


Figure 3.1
Targeted location for pulse laser detection of methane and carbon dioxide. © Sarah Dandois and Élodie Ouellet-Belleau.

4. Discovering Viruses in Northern Lakes and Ponds

Selected research highlights

Little is known about the viruses that infect the microbial communities of Arctic thermokarst ponds and lakes, yet these viruses can control microbial populations and influence biogeochemical cycles.

4.1 A first viral diversity study of thermokarst ponds focused on myoviruses and chloroviruses using amplicon sequencing. Results indicate that viral diversity varies by environmental type, and suggest that the composition of the bacterial host community is influenced by environmental filtering, which in turn contributes to viral diversity in different landscape types (Lévesque et al., 2018).

4.2 Viral communities in thermokarst lakes exhibit seasonal differences. In addition to identifying 351 distinct viral populations, a research team observed that viral diversity changes drastically between summer and winter, suggesting a significant change in the viral community between the two seasons (Girard et al., 2020).

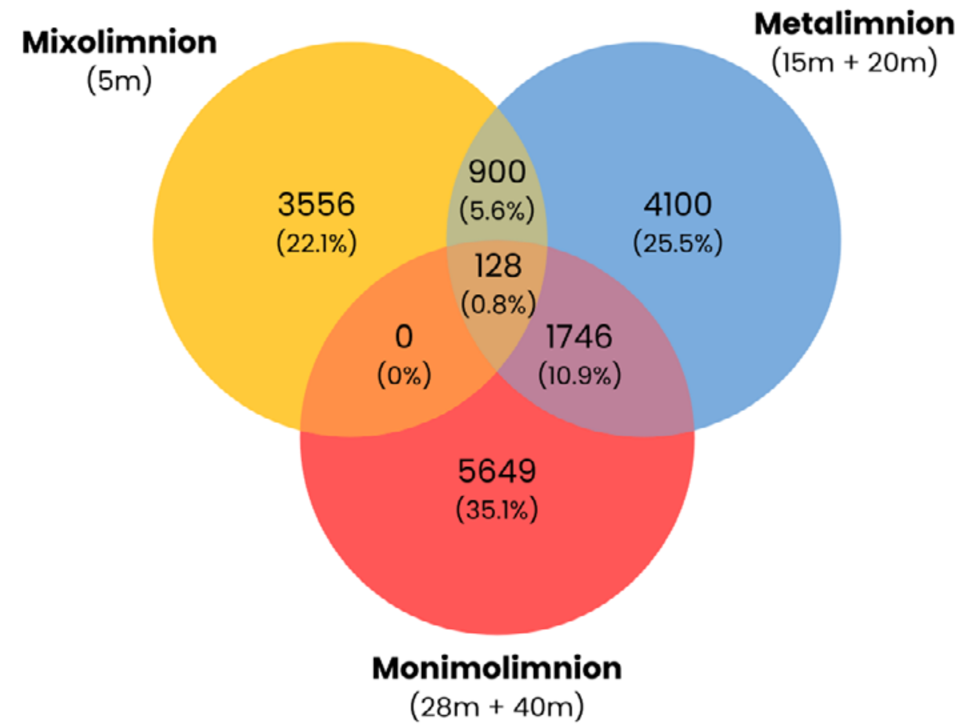


Figure 4.3
Proportions of viral operational taxonomic units (vOTUs) shared among the lake strata. vOTUS are individual sequences representing a group of highly similar viral contigs. The percentage of shared vOTUs for each section is shown in parentheses. Figure adapted from Labbé et al., 2020, licensed under CC BY 4.0.

4.3 In a highly stratified High Arctic lake, deep-layer viral communities were more diverse and abundant than in the surface layers and are different from known viral sequences (Figure 4.3). These results demonstrate the complexity and uniqueness of viral communities in a changing environment (Labbé et al., 2020).

4.4 Phage discovery is still in its early stage. The bacterial hosts of new phages in various environments can now be predicted using a bioinformatics approach, which takes advantage of the information in CRISPR-Cas systems (Dion et al., 2020; Dion et al., 2021). With this significant breakthrough, it was possible to survey CRISPR loci in all bacterial genomes in the National Center for Biotechnology Information (NCBI) database and thus increase the number of spacers available for homology searches. This data set is now available on the platform CRISPR Spacers Database.

5. Arctic Lakes as Sentinels of Change

Selected research highlights

Arctic lakes are particularly sensitive to climate change, because of the role that ice cover plays in their structure and function.

5.1 Previously covered by a thick, continuous ice cover, polar lakes will likely experience an irregular ice regime and unstable limnological conditions that vary from year to year (Figure 5.1; Bégin et al., 2021a). The loss of summer ice cover affects water column properties and benthic light conditions. The functioning of these ecosystems could be profoundly altered, particularly regarding energy and gas exchange with the atmosphere (Bégin et al., 2021b).

5.2 Freshwater ice cover plays an underrated role in storing carbon and transforming the biogeochemical cycles of Arctic and boreal lakes. Melting ice releases a significant number of particles and compounds that would influence the productivity of these lakes (Imbeau et al., 2021).

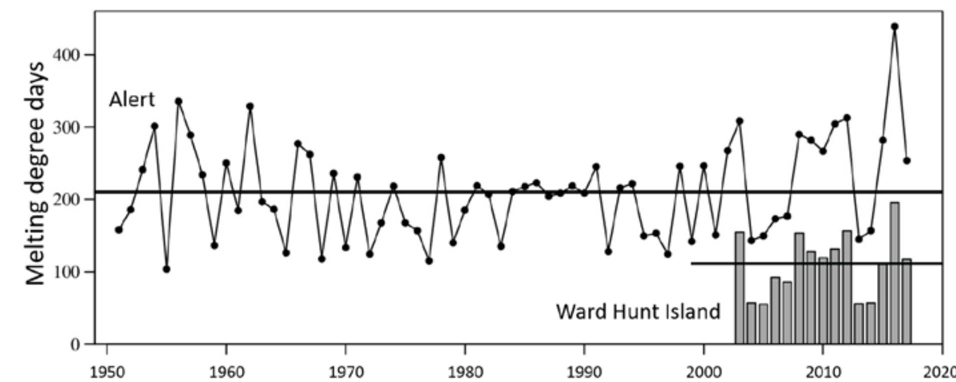
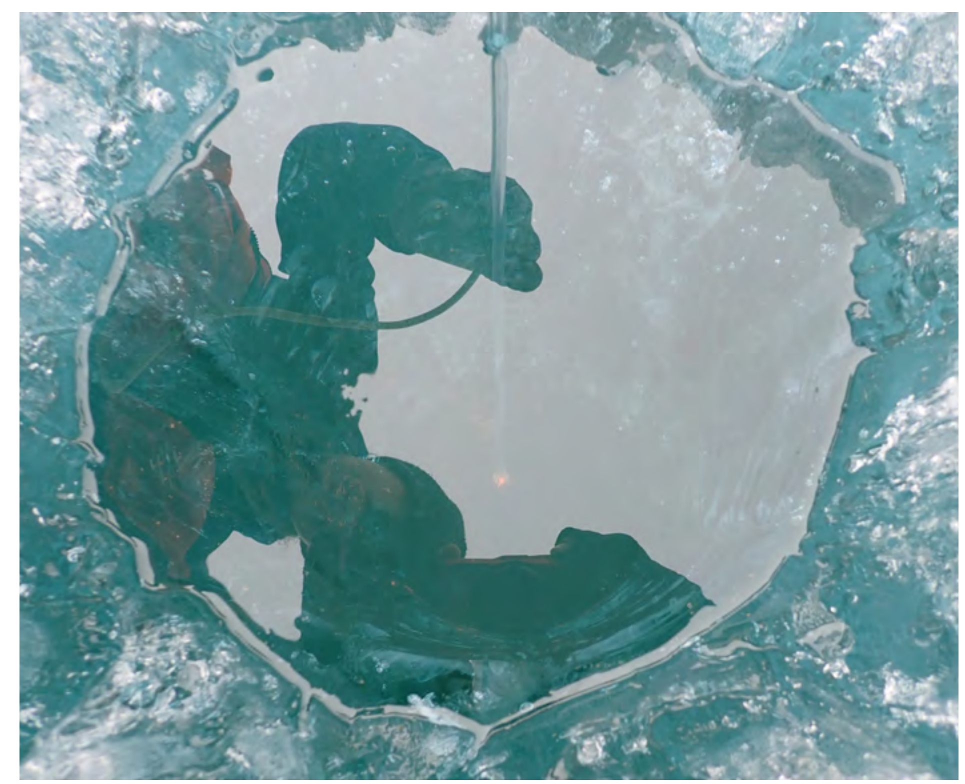
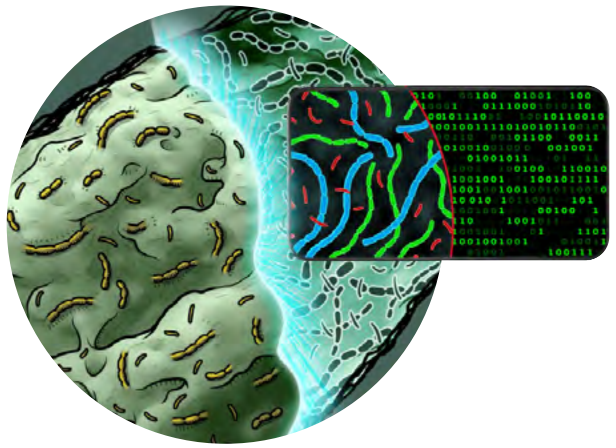


Figure 5.1
Melting degree days at Alert (black line and points) and Ward Hunt Island (bars). The horizontal lines are the overall average values for the two records. Figure taken from Bégin et al., 2021a, licensed under CC BY-NC 4.0

5.3 With climate warming, fewer Arctic lakes will be frozen to the bottom in winter. The presence of water at the bottom of lakes has promoted anaerobic metabolism in cyanobacterial biofilms, increasing the production of the potent greenhouse gas methane (Mohit et al., 2017).





6. New Technologies to Monitor Arctic Lakes

Selected research highlights

The development of new technologies is important for monitoring the physicochemical and biological characteristics of Arctic lakes.

6.1 Sensors can be deployed in the field to continuously monitor water quality in Arctic environments using self-sustaining and high-performance energy sources based on a microbial fuel cell of bacteria contained in the northern soil. Such a fuel cell has been developed and tested for different temperature profiles allowing a fourfold increase in generated power and a doubling of output current (Gong et al., 2021; Gong et al., 2022; Brochu et al., 2021; Amirdehi et al., 2020).

6.2 The synthesis of the PPDT2FBT-conjugated polymer, using water compatible direct(hetero)arylation polymerization (DHAP) has enabled the fabrication of organic photovoltaic devices with a low environmental footprint (Mainville et al., 2020). These new devices could soon power an interconnected system of instruments for measurement in Arctic and subarctic regions (Mainville, 2022).

6.3 A microfluidic platform was developed for live cell imaging and automated species detection in Arctic cyanobacteria biofilms. This technology combines hyperspectral imaging and deep learning and provides a versatile platform for studying cyanobacteria biofilms, which are significant components of lakes and rivers in polar regions (Deng et al., 2021).

7. Changing Hydrologic Regimes

Selected research highlights

Similar to lakes, rivers and groundwater in northern regions are also impacted by environmental changes. For example, permafrost degradation causes an increase in active layer thickness and alters groundwater flow patterns. Understanding the underlying mechanisms is essential to better understand ongoing changes in permafrost environments.

7.1 A circumpolar analysis of 336 rivers over the 1970–2000 period showed that increases in active layer thickness are generally associated with decreases in groundwater flow to rivers. Thawing permafrost leads to increased hydrologic connectivity, increasing the diversity of flow paths and, thus, drainage areas (Sergeant et al., 2021).

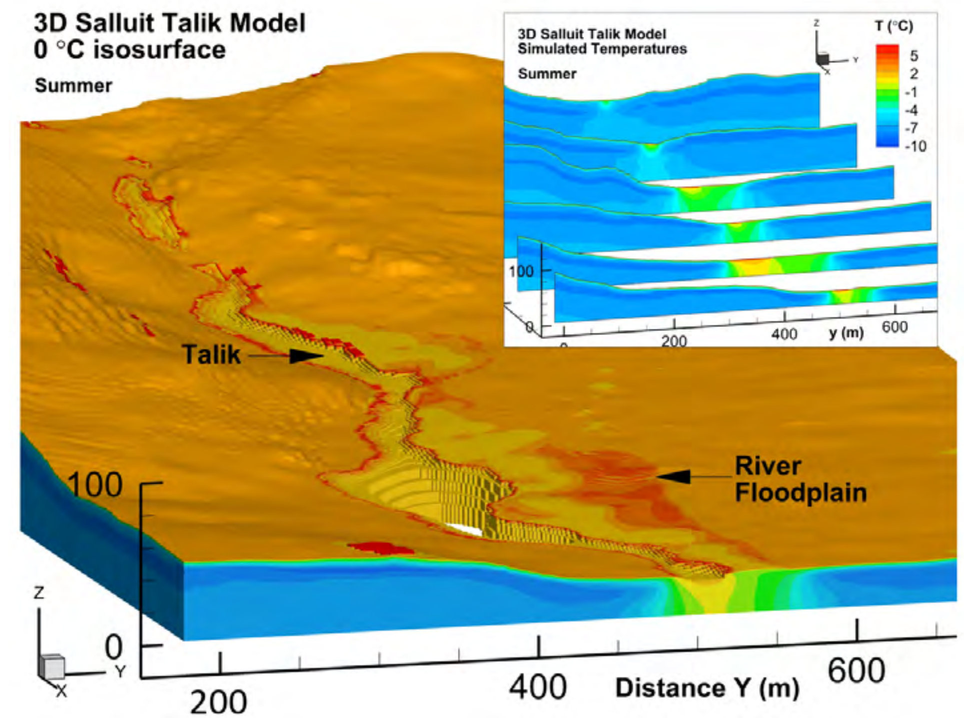


Figure 7.2
Three-dimensional perspective showing simulated temperatures around a talik in the continuous permafrost of the Kuuguluk River valley, Salluit, Nunavik. © John Molson

7.2 Combined with a 3D numerical model, field data provided key information on the processes governing groundwater flow and heat transport in and around a river-talik system in continuous permafrost areas (Figure 7.2). A better understanding of these processes is essential to better understand icing formation (also known as aufeis) and to assess the potential of talik aquifers as drinking water sources in northern communities (Liu et al., 2021; Liu et al., 2022).

8. Changes in the Snowpack

Selected research highlights

Snow is an essential component of Arctic and subarctic ecosystems. The physical and biological characteristics of snow are changing, with consequences for surface energy balance, snowpack use as habitat, and associated microbial communities.

8.1 The subarctic snowpack can adopt two very different configurations: in years of thick snow it behaves like an alpine snowpack (i.e., density decreases with snow height), while in years of thin snow it behaves like an Arctic snowpack (reverse density profile). Alpine snow effectively shields the ground from the cold, allowing the ground to maintain a significantly warmer temperature (several °C) than when the snow is of Arctic type (Lackner et al., 2021).

8.2 An increase in snow hardness and density is expected. These changes are likely to affect the survival and population dynamics of lemmings sheltering in the snowpack during the harsh Arctic winter. The increased frequency of freeze-melt and rain-on-snow events will impact the digging performance and amount of effort expended by lemmings (Figure 8.2), a keystone species in Arctic food webs (Poirier et al., 2021).

8.3 Several technological advances have emerged to automatically measure the physical properties of snow and, in particular, its density. Theoretical developments validated by laboratory measurements have demonstrated that density measurements of a porous material like snow could be taken with a laser technology (Libois et al., 2019). The next step is to deploy a prototype in the High Arctic that continuously measures the evolution of snow density throughout the winter.

8.4 A study in the Canadian High Arctic found that microbial communities are distinct between different habitats. However, 30% of phylotypes are shared along the hydrological continuum, demonstrating that many taxa originally found in snow remain active downstream. These results indicate that changes in snow precipitation associated with climate warming will affect microbial community structure across snowpack-connected habitats (Comte et al., 2018).

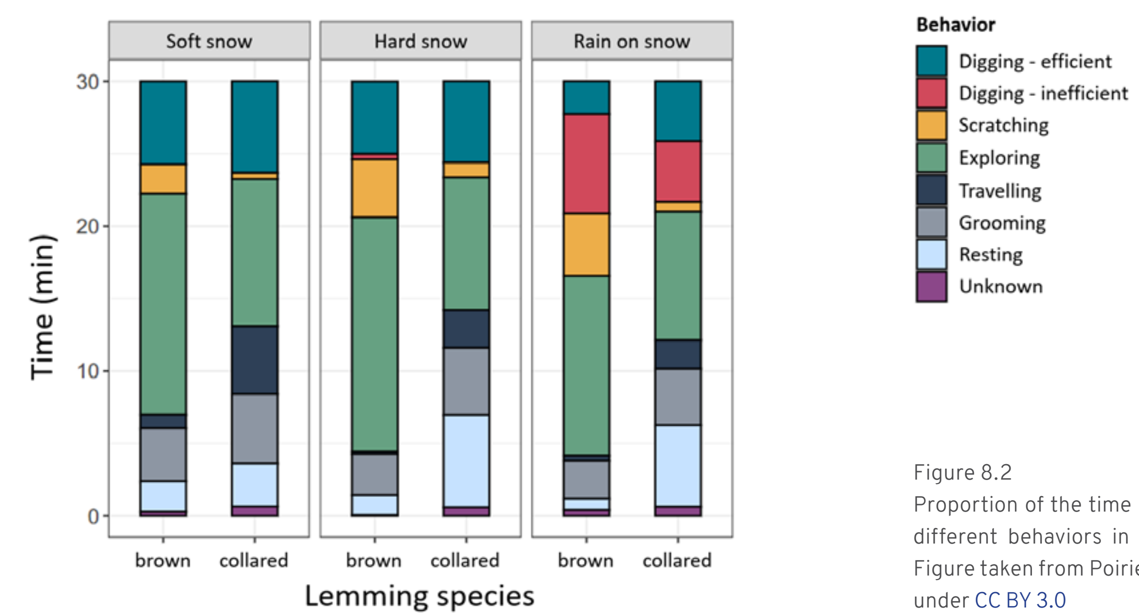


Figure 8.2
Proportion of the time lemmings spent doing different behaviors in different snow types. Figure taken from Poirier et al., 2021, licensed under CC BY 3.0

9. Importance of Cryobiodiversity in a Climate Warming Context

Selected research highlights

Climate warming threatens the existence of several Arctic habitats, resulting in a reorganization of the communities that inhabit these habitats, particularly the microbial communities. It is important to better understand and preserve the biodiversity associated with these environments, and to study the properties of organisms adapted to these extreme environments.

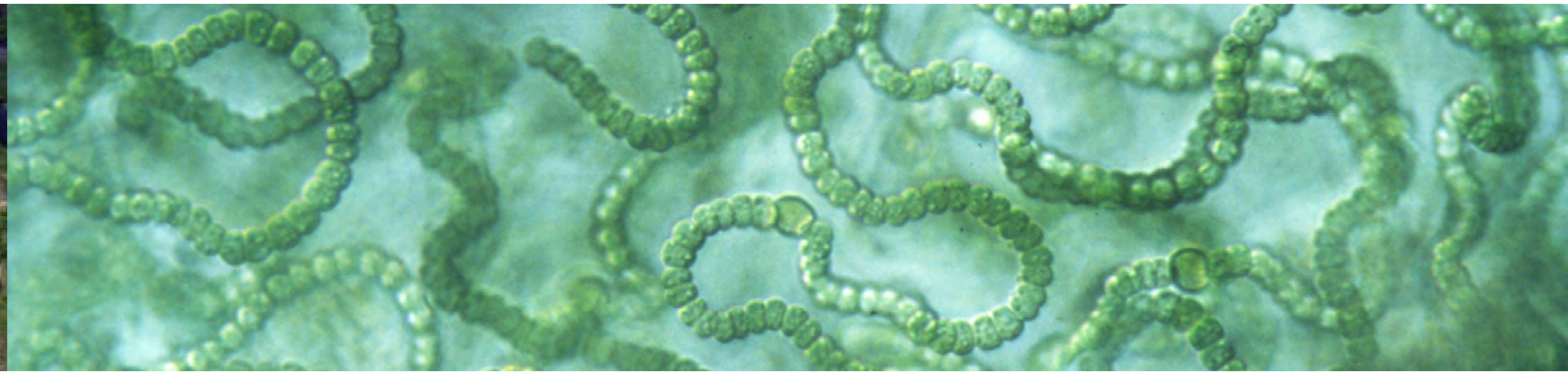
9.1 A collaborative study with the National Institute of Polar Research has identified new psychrophilic yeasts in a retreating glacier in the Canadian High Arctic. These yeasts exhibit unique characteristics, including the ability to grow at sub-zero temperatures and in a vitamin-free environment (Tsuji et al., 2019a; Tsuji et al., 2019b).

9.2 The unique biodiversity associated with glaciers is at risk owing to the loss of these habitats. Yet fungal species in these habitats play a fundamental role in the carbon and nutrient cycle and have distinctive biochemical characteristics (Tsuji et al., 2022). There is a need to better understand and preserve samples of this cryobiodiversity, and protect important regions, including the Last Ice Area (Vincent and Mueller, 2020).

9.3 Research teams have used the Biodiversity Cryobank of Canada to preserve biofilm samples from Arctic lakes. The samples are placed in freezers cooled with liquid nitrogen to below -160°C. This temperature preserves the information contained in the samples' DNA molecules in perpetuity. As the Canadian Arctic rapidly warms, these samples provide a valuable record of the genetic diversity of High Arctic freshwater microbiomes (Bull and Vincent, 2020).

9.4 The diverse microbial communities from thermokarst lake sediments were analyzed and cultured to isolate selected strains. One of the strains of *Pseudomonas extremaustralis* shows an ability to produce a polysaccharide with biotechnological potential, and could become a sustainable alternative to commercial polymers (Finore et al., 2020).

9.5 An initial genomic analysis of polar Nostoc cyanobacteria revealed a higher diversity of secondary metabolites than strains found in temperate environments. These metabolites could be investigated for their potential value, in particular through bioactive compounds for drug development. A CRISPR-Cas analysis also demonstrated that virus-cyanobacteria interactions are diverse in the Arctic and that viruses play a key role in this region's microbial diversity (Jungblut et al., 2021).



Research Projects Cited in this Chapter

The knowledge and technological advances referenced in this chapter were generated by several Sentinel North interdisciplinary research teams. These scientific contributions were gathered from the projects listed below, which involved, in addition to the principal investigators, numerous researchers, graduate students, postdoctoral fellows, research professionals, collaborators, partners from northern organizations and national and international partners from the public and private sectors.

- Characterization and modelling of the key interrelationships of northern water systems under climatic, geosystemic, and societal pressures

  Principal Investigator: René Therrien (Dept. of Geology and Geological Engineering)

- Comprehensive environmental monitoring in the North: From molecules to microorganisms

  Principal Investigator: Jacques Corbeil (Dept. of Molecular Medicine)

- Deploying light-based sensing technologies to monitor climate active gases in a mutating Arctic (BOND2.0)

  Principal Investigators: Martin Bernier (Dept. of Physics, Physical Engineering, and Optics), Daniel Nadeau (Dept. of Civil and Water Engineering)

- Developing light-based sensing technologies to monitor climate active gases in a mutating Arctic (BOND)

  Principal Investigator: Réal Vallée (Dept. of Physics, Physical Engineering, and Optics)

- Doing things differently: An atlas of best practices and opportunities for culturally acceptable and sustainable living environments in Nunavik

  Principal Investigators: Geneviève Vachon (School of Architecture), Michel Allard (Dept. of Geography)

- Innovative optical systems to track winter life in the cryosphere

  Principal Investigator: Gilles Gauthier (Dept. of Biology)

- Last ice microbiomes and Arctic ecosystem health

  Principal Investigators: Alexander Culley (Dept. of Biochemistry, Microbiology and Bio-informatics), Warwick Vincent (Dept. of Biology)

- Optogenetics investigation of microbiota influence on brain development and epigenetics

  Principal Investigators: Paul De Koninck (Dept. of Biochemistry, Microbiology and Bio-informatics), Sylvain Moineau (Dept. of Biochemistry, Microbiology and Bio-informatics)

- Photonic ultimate sensing (pulse) and monitoring of permafrost environments

  Principal Investigators: Sophie Larochelle (Dept. of Electric and Computer Engineering), Richard Fortier (Dept. of Geology and Geological Engineering)

- Printed solar cells for small remote instruments

  Principal Investigator: Mario Leclerc (Dept. of Chemistry)

- Sentinel microbiomes for Arctic ecosystem health

  Principal Investigators: Daniel Côté (Dept. of Physics, Physical Engineering, and Optics), Warwick Vincent (Dept. of Biology)

- Partnership research chair on Permafrost in Nunavik

  Chairholder: Pascale Roy-Léveillée (Dept. of Geography)

- Sentinel North Research Chair in Aquatic Environmental Geochemistry

  Chairholder: Raoul-Marie Couture (Dept. of Chemistry)

Research projects cited in this chapter

Some results presented in this chapter are also drawn from research projects conducted by recipients of Sentinel North Excellence scholarship and postdoctoral fellowship awards.

- Développement de capteurs distribués dans une fibre multicœurs pour la mesure de contraintes

  Tommy Boilard (Master's Scholarship)

- Développement de cellules solaires organiques imprimables à base de nouveaux matériaux π-conjugués de type n

  Mathieu Mainville (Ph.D. Scholarship)

- Étude des interactions phages-bactéries dans le système gastro-intestinal

  Moïra Dion (Ph.D. Scholarship)

- Fibrage et fonctionnalisation laser de verres moyens infrarouges germano-gallates de baryum pour la détection de gaz climatiquement actif dans le Nord

  Théo Guérineau (Postdoctoral Fellowship)

- Virus aérosols libérés de la cryosphère en fonte: des microorganismes sentinelles du changement dans le Nord

  Catherine Girard (Postdoctoral Fellowship)

Sentinel North has developed partnerships with leading international institutions to conduct innovative and interdisciplinary research projects. The following joint collaborative projects have contributed to the results of this chapter.

- Development of compact laser sources operating in the mid-infrared spectral region for remote gas sensing systems

  Principal Investigators: Martin Bernier (Dept. of Physics, Physical Engineering, and Optics), Bernard Dussardier (Institut de physique de Nice, Université Côte d'Azur)

- Joint International Research Unit Québec-Brazil in Photonics Research

  Director: Younès Messaddeq (Dept. of Physics, Physical Engineering, and Optics)
  São Paulo State University, Brazil
  Associated with the CERC in Photonic Innovations

- Joint International Research Unit for Chemical and Biomolecular Research of the Microbiome and Its Impacts on Metabolic Health and Nutrition

  Director: Vincenzo Di Marzo (Dept. of Medecine)
  National Research Council, Italy
  Associated with the CERC in the Microbiome-Endocannabinoidome Axis in Metabolic Health

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Ongoing Sentinel North Research Projects

Several research projects supported by Sentinel North and through joint funding initiatives are ongoing as part of the second phase of the program (2021-2025). These projects, listed hereunder, continue to fill fundamental gaps in our scientific knowledge of the changing North.

- Deploying light-based sensing technologies to monitor climate active gases in a mutating Arctic (BOND2.0)

  Principal Investigators: Martin Bernier (Dept. of Physics, Physical Engineering, and Optics), Daniel Nadeau (Dept. of Civil and Water Engineering)

- Development of compact laser sources operating in the mid-infrared spectral region for remote gas sensing systems

  Principal Investigators: Martin Bernier (Dept. of Physics, Physical Engineering, and Optics), Bernard Dussardier (Institut de physique de Nice, Université Côte d'Azur)
  Project jointly funded by Sentinel North and Université Côte d'Azur

- Doing things differently: An atlas of best practices and opportunities for culturally acceptable and sustainable living environments in Nunavik

  Principal Investigators: Geneviève Vachon (School of Architecture), Michel Allard (Dept. of Geography)

- Impacts of climate change and browning on salmonid oxythermal habitat and greenhouse gas emissions in Arctic regions

  Principal Investigator: Isabelle Laurion (Eau Terre Environnement Research Centre, Institut national de la recherche scientifique)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Last ice microbiomes and Arctic ecosystem health

  Principal Investigators: Alexander Culley (Dept. of Biochemistry, Microbiology and Bio-informatics), Warwick Vincent (Dept. of Biology)

- QAUJIKKAUT: An on-line advanced foresight tool of extreme meteorological events and natural hazards in Nunavik using real-time access to the SILA network of climate and environmental observatories

  Principal Investigators: Richard Fortier (Dept. of Geology and Geological Engineering), Thierry Badard (Dept. of Geomatics)

- Partnership research chair on Permafrost in Nunavik

  Chairholder: Pascale Roy-Léveillée (Dept. of Geography)

- Sentinel North Research Chair in Aquatic Environmental Geochemistry

  Chairholder: Raoul-Marie Couture (Dept. of Chemistry)

- Sentinel North Partnership Research Chair on Northern Infrastructure

  Chairholder: Jean-Pascal Bilodeau (Dept. of Civil and Water Engineering)

- Joint International Research Unit Québec-Brazil in Photonics Research

  Director: Younès Messaddeq (Dept. of Physics, Physical Engineering, and Optics)

- Joint International Research Unit for Chemical and Biomolecular Research of the Microbiome and Its Impacts on Metabolic Health and Nutrition

  Director: Vincenzo Di Marzo (Dept. of Medecine)

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Acknowledgment
The following research team members contributed to the review
of the scientific highlights presented in this chapter:

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Jesse Greener, Théo Guérineau, Jean-Michel Lemieux, Sylvain Moineau,
Mathilde Poirier, Pascale Roy-Léveillée, Warwick Vincent

We also thank Emmanuel L'Hérault and Mary Thaler for their comments
on the introduction.

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Martin Lipman © Canadian Museum of Nature	73
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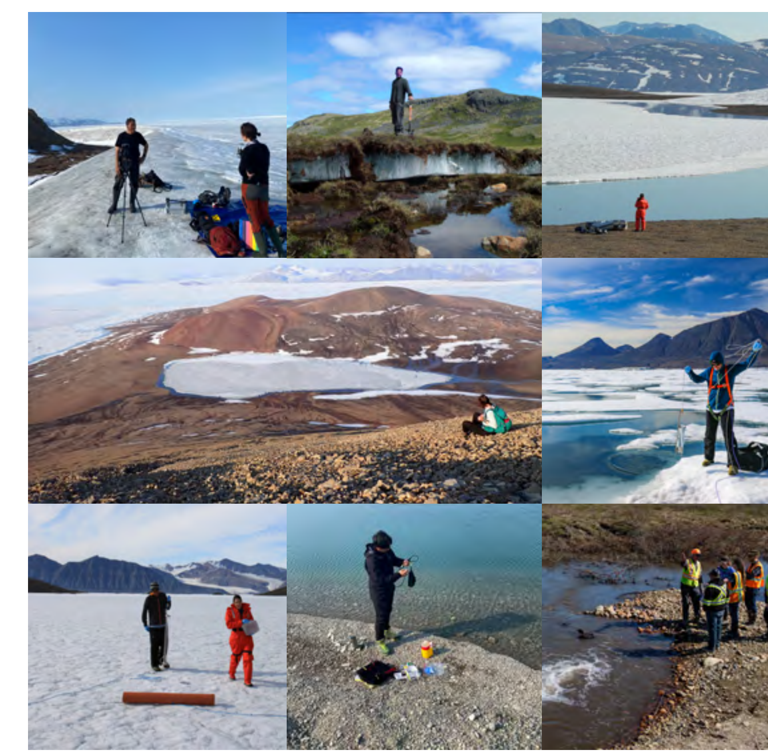


CHAPTER 3

Terrestrial Ecosystem Dynamics and Responses to Change

From Molecules to Food Webs: Northern Terrestrial Ecosystem Dynamics in Response to Environmental Changes

Introduction

Arctic and subarctic terrestrial ecosystems face significant ecological changes in response to climate shifts. Repeated aerial photograph comparisons and Normalized Difference Vegetation Index (NDVI, a proxy of primary production) analyses derived from satellite images reveal widespread yet heterogenous greening of the Arctic and subarctic (AMAP, 2021), which in turn impacts other biotic and abiotic components of the landscape. However, the consequences of these changes are diverse among species and ecosystems, leading to potential trophic interaction disruptions. In this context, it becomes necessary to increase our understanding of the effects of climate change at each level of organization, from the moleculome to the ecosystem, as well as between different ecosystems.

The harsh Arctic and subarctic environment imposes unique stresses on growing organisms such as micro-organisms, lichens, mosses and other plants. The unique biochemical adaptations they have developed to protect themselves from low temperatures, strong winds, nutrient-poor soils and high UV radiation include bioactive molecules with pharmaceutical applications (Tian et al., 2017; Carpentier et al., 2017; Bérubé et al., 2019, Séguin et al., 2023). The “moleculome”, or the ensemble of phytochemicals that a plant produces, has been described for a very small proportion of species in Canada’s north (N. Voyer, personal communication), and there is an urgent need to expand this work as climate change transforms growth and distribution patterns.

Characterized by low and slow-growing vegetation (Payette et al., 2018), the tundra biome is vulnerable to change. Lichens, in particular, are threatened by the rapid expansion of erect shrub species. Dwarf birch (*Betula glandulosa*) and other shrubs are expanding into the tundra because of factors that include warming temperatures, changes in snow dynamics, permafrost thaw, disturbances, and herbivory grazing (Mekonnen et al., 2021). This greening trend, also called shrubification, occurs at the expense of the natural flora of slow-growing lichens in the tundra (Chagnon and Boudreau, 2019) and may affect animal species which use both lichen and dwarf birch as a food source at different times of year (Béland, 2022). The growth of shrub vegetation also changes the landscape in fundamental ways, for example, by altering its reflective albedo and creating a canopy layer that changes soil temperature, permafrost depth, hydrology and micro-habitats for numerous animal species (Pelletier et al., 2018; Young et al., 2020; Domine et al., 2022).

While climate change impacts species at the individual level, it will also impact the network of trophic links relating the different species within an ecosystem. One challenge that ecologists face today is to understand how communities forming a complex interaction network will reorganize following the response of individual species to climate changes (Woodward et al., 2010). A spatial or temporal mismatch may separate previously interacting species (Schleuning et al., 2020), while novel interactions may appear due to new spatial co-occurrences (Gilman et al., 2010). In the Canadian High Arctic, for instance, several tundra vertebrates have shown little response to climate warming compared to plants and arthropods (Gauthier et al., 2013). Some species might migrate faster than others (Svenning et al., 2014), breaking the coherence of interaction networks. Trophic interactions can modify the effects of disturbances such as climate change and transfer effects to distant groups of organisms that would not have been affected otherwise (Labadie et al., 2021). Therefore, more studies integrating multiple trophic levels and temporal dynamics are needed to improve our understanding of species distribution and how they will respond to global changes (Woodward et al., 2010).

Through modelling, researchers can apply the knowledge they gain about plant and animal populations to pressing questions about the vulnerability and resilience of Arctic and subarctic ecosystems. Models can predict the overall stability of an ecosystem (Brose et al., 2019) or the effects that different climate change scenarios will have on species distributions (Bourderbala et al., 2023). Models must include seasonal variation to predict future changes (Tonkin et al., 2017), particularly in Arctic food webs where migratory species play a major role (Hutchison et al., 2020). However, as a model's complexity increases to represent the realities of real-world ecosystems, the mathematical challenges increasingly grow. Researchers from diverse disciplines, including physicians and mathematicians, have joined together with ecologists to find solutions, such as using spectral graph theory to reduce model complexity (Laurence et al., 2019) or predicting changes in complex systems using deep learning and neural networks (Laurence et al., 2020).

Whether in the greening of the Arctic tundra (Mekonnen et al., 2021) or the changing trophic network (Labadie et al., 2021), the transformation of Arctic and subarctic terrestrial ecosystems caused by climate change is visible and accelerating. The work by Sentinel North researchers described in this chapter looks at these effects from molecules to population dynamics and the broader web of interacting species. Above all, this research seeks to respond to urgent challenges of conservation and resource use by evaluating current methods to monitor biodiversity and wildlife populations (LeTourneux et al., 2022; Terrigeol et al., 2022; Bolduc et al., 2023), developing innovative tools (Bolduc et al., 2022) and working jointly with northern communities, many of which rely on traditional harvesting activities (e.g., Séguin et al., 2023; LeTourneux et al., 2021; Bates et al., 2021). Facing the challenges of climate change and biodiversity loss requires a sophisticated and integrated understanding of these terrestrial ecosystems that comes from Sentinel North's interdisciplinary approach.

KEY WORDS:
Food Webs, Shrubification, Moleculome, Modelling, Migration, Tundra, Population Dynamic

1. Northern Chemodiversity: A Distinctive Molecular Signature

Selected research highlights

The plant species that colonize Arctic and subarctic environments carry a unique yet unknown chemodiversity that could reveal molecules with medicinal properties of interest. However, this chemodiversity is threatened by climate change, which can alter the distribution of plant species and their environments.

1.1 The first ever phytochemical investigation of the volatile fraction of the dwarf birch (*Betula glandulosa*) was recently performed, revealing a molecular composition that included terpenoids, fatty acid derivatives and phenylpropanoids (Figure 1.1), as well as a volatile metabolite composition different from its *Betula* genus conspecifics. As this shrub species is an important food source for many herbivores and a structuring element of the landscape, a better knowledge of the species' molecular composition is needed to understand some aspects of its functional role in the ecosystem (Séguin et al., 2021).

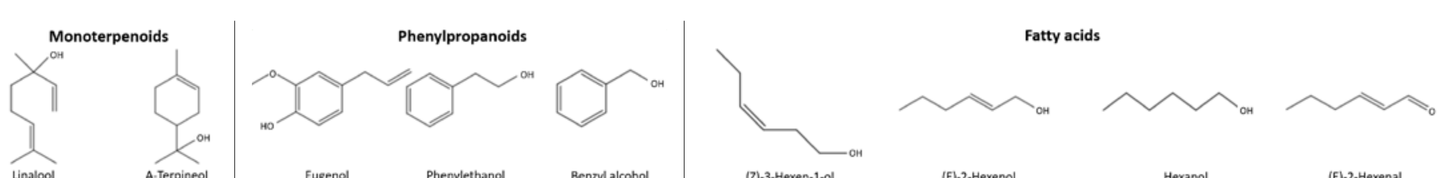


Figure 1.1
Structures of the main metabolites of Betula glandulosa volatile extracts.
© Jean-Christophe Séguin

1.2 Two new dibenzofurans and 11 other lichen metabolites were isolated and identified through phytochemical studies on the lichen *Stereocaulon paschale*. Some of these metabolites showed promising antibacterial activity against the oral pathogenic bacteria *Porphyromonas gingivalis* and *Streptococcus mutans* (Carpentier et al., 2017).

1.3 The chemical synthesis of natural mortiamides from a fungus belonging to the genus *Mortierella* revealed promising activity of these molecules against the *Plasmodium falciparum* parasite, which is responsible for 50% of malaria cases. These results are particularly noteworthy because of the increased resistance of *Plasmodium sp.* to existing medications. Work is ongoing to synthesize analogues of mortiamide D with increased efficacy against *P. falciparum* (Bérubé et al., 2019).

1.4 A molecule with antiparasitic properties was isolated from essential oil extracts from dwarf Labrador tea leaf (*Rhododendron subarcticum*) in Nunavik. This molecule could be useful against parasitic infections, notably malaria (Séguin et al., 2023). Furthermore, analysis of seasonal and geographical variations in this species' moleculome will enable us to determine the best harvesting periods and sites to maximize health benefits..

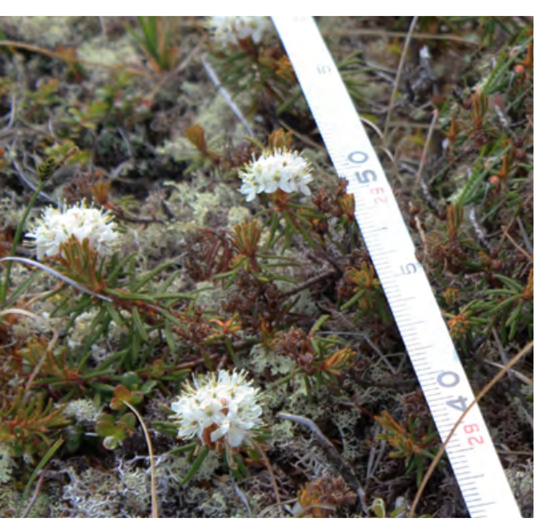
Impact of Latitude on Lichen Bacterial Diversity

A research team examined the bacterial diversity of northern lichens. This research showed that star-tipped reindeer lichen (*Cladonia stellaris*) found in northern lichen woodlands had significantly higher bacterial diversity and quantity than those found in southern lichen woodlands and that only one of these bacteria (*Methylorosula polaris*) was common to both regions. These differences in bacterial communities between the two environments remain poorly understood at present but could be related to different colonization processes or a greater presence of bacteria in northern soils (Alonso-Garcia et al., 2022).

2. Greening: Multiple Impacts in an Interconnected Environment

Selected research highlights

The expansion of shrub species, or shrubification, leads to a major restructuring of plant communities, particularly due to the presence of a shrub-formed canopy that modifies local biotic and abiotic conditions. Impacts of this transformation of the landscape occur at various levels of organization, from species to the functioning of Arctic and subarctic ecosystems.



2.1 Shrub cover has negatively impacted lichen abundance and species richness in the boreal forest-tundra ecotone. By changing the distribution of different lichen species across the landscape, shrubification could change the surface albedo, which has a significant impact on climate (Chagnon and Boudreau, 2019).

2.2 Observed and predicted changes in plant communities within the summer and winter ranges of migratory caribou (*Rangifer tarandus*) will affect this ecologically and culturally important herbivore. The decrease in lichen cover in favour of shrubs is detrimental to the cervid's dependence on this resource for winter food (Chagnon and Boudreau, 2019), but may also result in more and better-quality summer food resources, such as dwarf birch or *Carex* sp.

2.3 Camera collars used on 60 female migratory caribou showed that they foraged in wetlands during the early summer season (June and July) and in shrub areas in August. The 65,000 videos analyzed also demonstrated that the migratory caribou prefers to eat lichens, birches, willows and mushrooms. These results will help guide future management and conservation plans for this species in decline (Béland, 2022).

2.4 In the Tasiapik Valley, Nunavik, the higher vegetation cover has promoted groundwater recharge. A higher vegetation cover provides more shade and allows for trapping snow more efficiently, resulting in increased snow accumulation and a longer melting period. These results suggest that with accelerating climate change and associated permafrost thaw, vegetation growth will increase groundwater recharge in cold regions (Young et al., 2020).

2.5 The effect of shrub cover on permafrost thermal regulation is complex and varies with the season. It was shown that shrubs can cool the ground in winter by providing a thermal bridge through the snowpack. On the other hand, shrubs can warm the ground in spring when the branches absorb solar radiation and transfer heat to the ground (Figure 2.5). These results demonstrate the need to include thermal bridging processes in climate models to better predict greenhouse gas emissions associated with permafrost thaw (Domine et al., 2022).

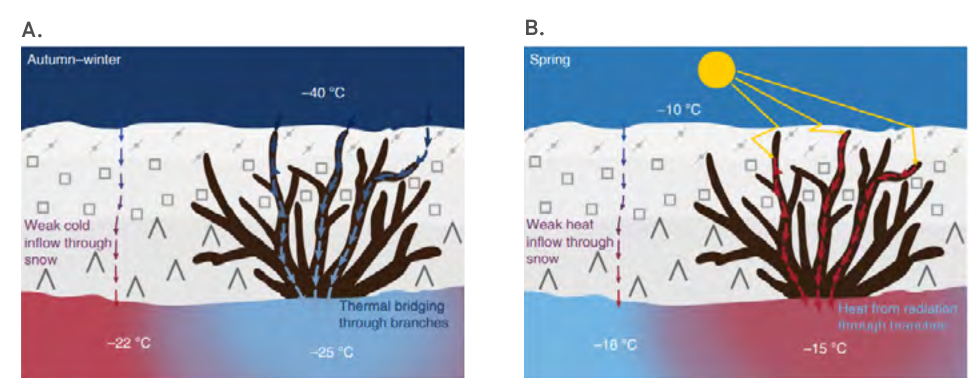


Figure 2.5
Thermal bridging through shrub branches in winter (a) and spring (b). Figure taken from Domine et al., 2022, licensed under CC BY 4.0.

"Borealization is becoming increasingly evident. The distributions of boreal species including moose, beaver, red fox and multiple boreal bird species have all been observed to be expanding into the Arctic tundra"

Speed et al., 2021

3. Changing Animal Communities

Selected research highlights

Northern ecosystems are sensitive to environmental changes, as increasing temperatures, shrub expansion and the arrival of boreal species change interactions among species. Densification and increased vertical growth of shrub species increase the amount of food and habitat available for herbivores while the arrival of boreal species modulates the interactions among existing species. Together, these changes can have unexpected impact.

3.1 A research team demonstrated that both bottom-up and top-down trophic interactions drive the functional and phylogenetic diversity patterns of vertebrate herbivores in the circumpolar Arctic (Speed et al., 2019). These results suggest that trophic interactions drive functional and phylogenetic diversity as strongly as climatic factors.

3.2 Indirect interactions within a food web may be critical to its dynamics. Although these indirect interactions are more difficult to quantify, a study demonstrated that the cascading effects of a defoliating insect in boreal ecosystems may ultimately increase the mortality rate of woodland caribou, particularly when human activities further disrupt the system (Figure 3.2). Such results are particularly crucial in the context of accelerating environmental change and anthropogenic disturbance (Labadie et al., 2021).

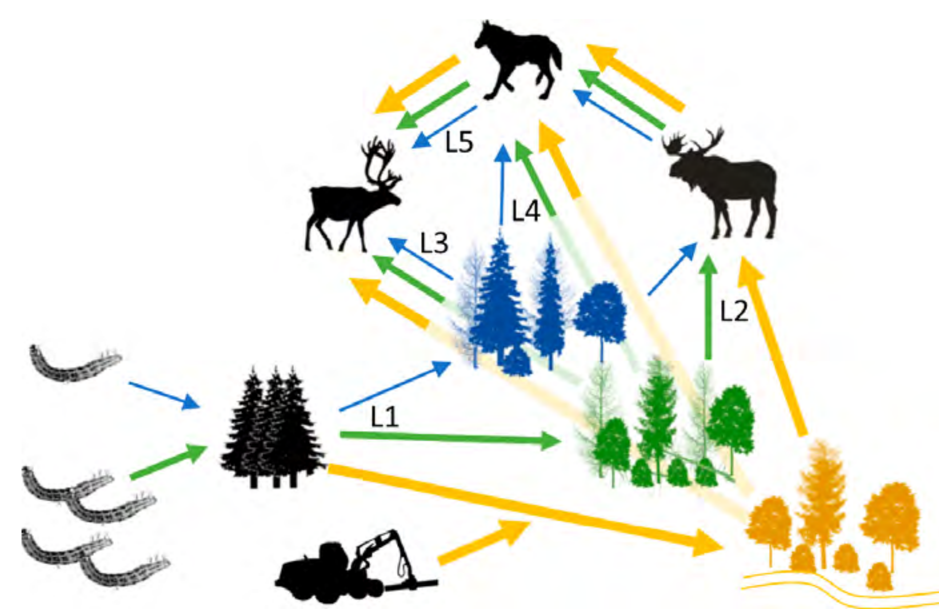


Figure 3.2
Trophic interactions illustrating the indirect effects of a defoliating insect of an early (blue arrows) and a later (green arrows) stage of an outbreak. The yellow arrows represent effects of salvage logging. Figure taken from Labadie et al., 2021, licensed under PNAS license.

4. New Technologies for Studying Lemmings: Another Step toward Understanding a Key Arctic Species

Selected research highlights

Studying Arctic animal species is often complex due to harsh climatic conditions and difficult-to-access study sites. This is especially true for lemmings, small mammals which are consumed by many different predators. Any change in their abundance and distribution can affect the entire food web they support. New technological developments are enabling us to understand the population dynamics and behaviours of these burrowing animals, particularly during the Arctic winter.

4.1 Ultra-light (1.59 g) photosensitive collars designed to record light variations while lemmings move can be used to infer the time spent in burrows. This technology shows promise for studying small mammal behaviour due to the miniaturization of the equipment (Bolduc et al., 2022).

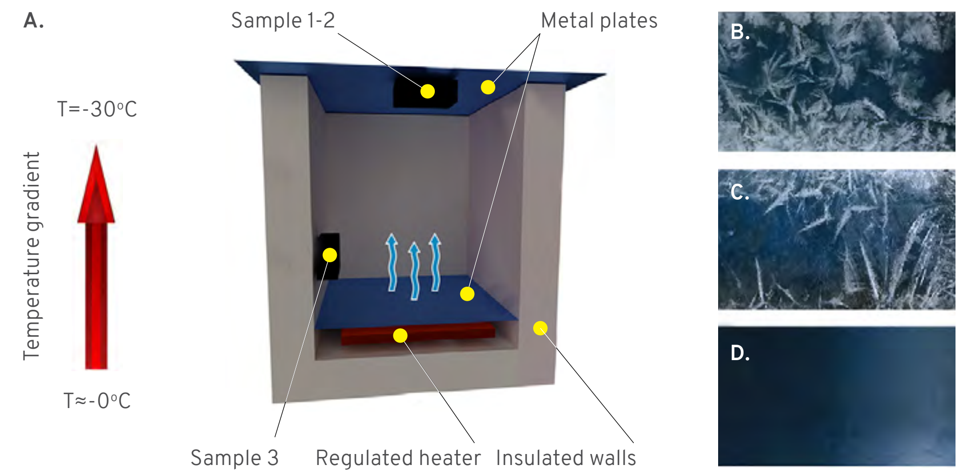
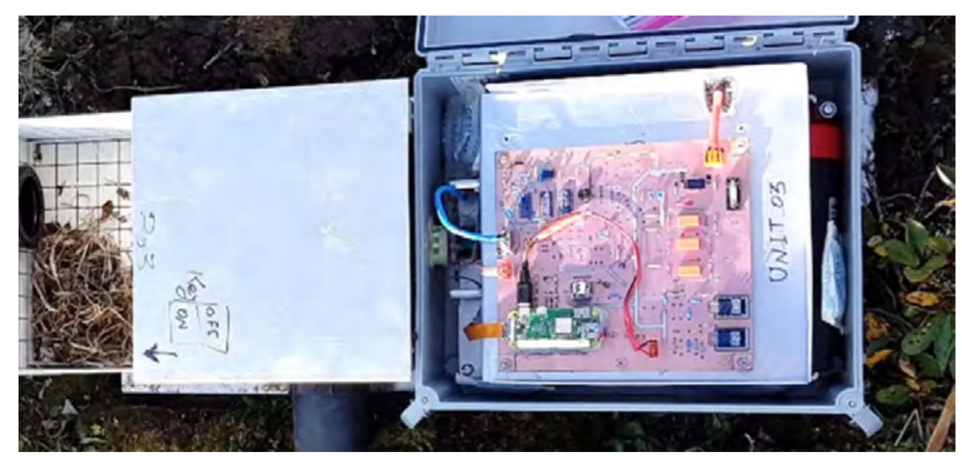


Figure 4.2
Frost formation was avoided by placing the glass sample on the lateral wall in a below freezing temperature setup. The experimental setup (a) shows frost formation on glass samples uncoated (b) and coated (c) with anti-fog solution when they are placed on top of the setup. An uncoated glass put on the lateral wall (d) shows little frost. Figure taken from Pusenkova et al., 2021, licensed under CC BY 4.0.

4.2 A research team has designed cameras capable of operating at temperatures ranging from - 20 °C to + 20 °C using a power-independent system to better understand lemming reproduction during winter. Modifications to the camera parameters have overcome problems with frost formation on the lens (Figure 4.2) and allowed for autofocus over a wide range of temperatures (Pusenkova and Galstian, 2020; Pusenkova et al., 2021).

4.3 The first complete sequence of winter lemming activity in the laboratory and then in the field on Bylot Island was conducted using an autonomous low-power camera system called ArcÇav. Among the new images obtained, the presence of young lemmings allows us to better define the timing of winter reproduction for these small mammals (Kalhor et al., 2021).



ArcÇav system

5. Predicting Ecosystem Interactions, Vulnerability and Resilience with New Modelling Approaches

Selected research highlights

The impacts of climate change are heterogeneous among species and ecosystems, with a high potential for disrupting biotic interactions, particularly by decoupling periods of high resource abundance from periods of high consumption and demand. New modelling approaches are required to better understand the effects of climate change, both on biotic interactions and ecosystem functioning.

5.1 At the regional level, both direct and indirect impacts of climate change were found on assemblage of over 100 species of birds and beetles in the boreal forest, and the magnitude of these impacts increased when their combined effect was considered. Similarly, this study suggests that the impact on the maintenance of biodiversity will be more pronounced at higher latitudes (Bouderbala et al., 2023).

5.2 A multi-seasonal model of predator-prey dynamics was developed and parameterized with empirical data collected on Bylot Island. This model can account for multiple equilibria in a simplified tundra food web. It highlighted indirect interactions not detected by a summer model, demonstrating the importance of incorporating seasonality for understanding food webs (Hutchison et al., 2020).

5.3 Food web structure can provide information about the community's ability to cope with a disturbance. However, collating the full range of relationships among a community's species is daunting. A predator-trait model was developed to overcome these difficulties, enabling us to better understand and predict differences in food web structure, community stability and ecosystem functioning (Brose et al., 2019).

5.4 Dynamical networks provide a comprehensive mathematical representation of complex systems, including ecosystems. A research team has developed a method that relies on spectral graph theory to reduce network complexity and thus predict overall system states. This approach is of both fundamental and practical interest for detecting critical transitions (Laurence et al., 2019).

5.5 A graph neural network approach, borrowed from the deep learning paradigm, has been developed to detect disturbances in a complex network, paving the way for studying complex real-world system resilience (Laurence et al., 2020).

6. Issues for Resource and Biodiversity Conservation

Selected research highlights

In light of accelerating climatic and anthropogenic pressures, it is essential to re-evaluate practices for monitoring ecosystem health and to propose new strategies.

6.1 Indicator species are commonly used to estimate local species richness. However, a research team has demonstrated that this technique is of limited value for monitoring and estimating biodiversity over large spatial dimensions. In Eastern Canada's boreal forest, for example, 57 indicator species would be needed to predict bird richness, demonstrating the need for new practices to monitor biodiversity (Terrigeol et al., 2022).

6.2 Some animal species are frequently tracked using collars. However, a long-term study found that the cumulative effect of collars and hunting pressure makes greater snow geese (*Anser caerulescens atlanticus*) more vulnerable to multiple sources of mortality (LeTourneux et al., 2022). Since 2021, these devices are no longer used for this species, posing new challenges for monitoring this overabundant population (P. Legagneux, personal communication).

6.3 The specific context of wide-scale lockdowns in the months following the global COVID-19 pandemic highlighted the fact that anthropogenic activities can have both positive and negative effects on resource and biodiversity conservation (Bates et al., 2021). During this lockdown period, hunting pressure on snow geese decreased by 54% compared to the previous year, thus positively impacting foraging efficiency and body conditions in geese (LeTourneux et al., 2021).

Research Projects Cited in this Chapter

The knowledge and technological advances referenced in this chapter were generated by several Sentinel North interdisciplinary research teams. These scientific contributions were gathered from the projects listed below, which involved, in addition to the principal investigators, numerous researchers, graduate students, postdoctoral fellows, research professionals, collaborators, partners from northern organizations and national and international partners from the public and private sectors.

- A network of automated sensors to monitor Arctic animals and environmental changes through advanced computational approaches

  Principal Investigators: Pierre Legagneux (Dept. of Biology), Audrey Durand (Dept. of Computer Science and Software Engineering)

- Comprehensive environmental monitoring and valorisation: From molecules to microorganisms

  Principal Investigator: Jacques Corbeil (Dept. of Molecular Medicine)

- Innovative optical systems to track winter life in the cryosphere

  Principal Investigator: Gilles Gauthier (Dept. of Biology)

- Interdisciplinary research to understand changing food-web dynamics and threats to food security in the northern boreal forest

  Principal Investigators: Daniel Fortin (Dept. of Biology), Jérôme Cimon-Morin (Dept. of Wood and Forest Science)

- Network analysis of umbrella and indicator species: Assessing the integrity of northern ecosystems

  Principal Investigator: Daniel Fortin (Dept. of Biology)

- The resilience of complex networks: Identifying critical indicators for efficient targeted interventions

  Principal Investigators: Patrick Desrosiers (Dept. of Physics, Physical Engineering, and Optics), Simon Hardy (Dept. of Biochemistry, Microbiology and Bio-informatics)

- Sentinel North Research Chair on the Applications and Theory of Network Analysis

  Chairholder: Antoine Allard (Dept. of Physics, Physical Engineering, and Optics)

- Sentinel North Research Chair on the Impact of Animal Migrations on Arctic Ecosystems

  Chairholder: Pierre Legagneux (Dept. of Biology)

Research Projects Cited in this Chapter

Some results presented in this chapter are also drawn from research projects conducted by recipients of Sentinel North Excellence scholarship and postdoctoral fellowship awards.

- Abondance et diversité des espèces lichéniques au Nunavik en contexte de changements climatiques
  Catherine Chagnon (Master's Scholarship)
- Production et caractérisation d'huiles essentielles issues de la nordicité
  Jean-Christophe Séguin (Master's Scholarship)
- Simulation de la dynamique du pergélisol en considérant l'advection de la chaleur par l'écoulement de l'eau souterraine
  Philippe Fortier (Master's Scholarship)
- Development of the smart LC shutter for the adaptive camera for subnival observation of lemmings
  Anastasiia Pusenkova (Ph.D. Scholarship)
- Influence de la prédation dans la répartition spatiotemporelle des espèces proies d'une communauté de vertébrés arctiques
  Frédéric Dulude-de Broin (Ph.D. Scholarship)
- Impact de changements récents de règlements de chasse sur la dynamique de population de la grande oie des neiges
  Frédéric LeTourneux (Ph.D. Scholarship)
- Impact des propriétés physiques de la neige sur les populations de lemmings
  Mathilde Poirier (Ph.D. Scholarship)
- Impact of wildfires on the diversity of lichen-associated viruses in a changing North
  Marta Alonso-Garcia (Postdoctoral Fellowship)
- Integrated modeling of the terrestrial water cycle in degrading permafrost environments
  Nathan Young (Postdoctoral Fellowship)

Sentinel North has developed partnerships with leading international institutions to conduct innovative and interdisciplinary research projects. The following joint collaborative projects have contributed to the results of this chapter.

- Characterization of essential oils from northern environments
  Principal Investigators: Xavier Fernandez (Institut de chimie de Nice, Université Côte d'Azur), Normand Voyer (Dept. of Chemistry)

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Ongoing Sentinel North Research Projects

Several research projects supported by Sentinel North and through joint funding initiatives are ongoing as part of the second phase of the program (2021-2025). These projects, listed hereunder, continue to fill fundamental gaps in our scientific knowledge of the changing North.

- A network of automated sensors to monitor Arctic animals and environmental changes through advanced computational approaches

  Principal Investigators: Pierre Legagneux (Dept. of Biology), Audrey Durand (Dept. of Computer Science and Software Engineering)

- Characterization of essential oils from northern environments

  Principal Investigators: Xavier Fernandez (Institut de chimie de Nice, Université Côte d'Azur), Normand Voyer (Dept. of Chemistry)
  Project jointly funded by Sentinel North and Université Côte d'Azur

- Dynamics of the Innu ancestral territory (Nitassinan) through the morpho-sedimentary and socio-cultural study of Lake Manicouagan (Reservoir)

  Principal Investigator: Patrick Lajeunesse (Dept. of Geography)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Ecogenomics of mining areas for sustainable Canadian North

  Principal Investigators: Véronic Landry (Dept. of Wood and Forest Science), Damase Khasa (Dept. of Wood and Forest Science)

- Impacts of climate change and browning on salmonid oxythermal habitat and greenhouse gas emissions in Arctic regions

  Principal Investigator: Isabelle Laurion (Eau Terre Environnement Research Centre, Institut national de recherche scientifique)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Interdisciplinary research to understand changing food-web dynamics and threats to food security in the northern boreal forest

  Principal Investigators: Daniel Fortin (Dept. of Biology), Jérôme Cimon-Morin (Dept. of Wood and Forest Science)

- Sentinel North Research Chair on the Applications and Theory of Network Analysis

  Chairholder: Antoine Allard (Dept. of Physics, Physical Engineering, and Optics)

- Sentinel North Research Chair on the Impact of Animal Migrations on Arctic Ecosystems

  Chairholder: Pierre Legagneux (Dept. of Biology)

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Figures licence

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Acknowledgment
The following research team members contributed to the review of the scientific highlights presented in this chapter:

Stéphane Boudreau, Steeve Côté, Florent Domine, Daniel Fortin, Marta Alonso-Garcia, Pierre Legagneux, Jean-Michel Lemieux and Normand Voyer.

We also thank Pierre Legagneux for his comments on the introduction.

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CHAPTER 4

Diet, Metabolic Health and Food Insecurity

Shedding Light on the Connections between Diet, Metabolic Health and Food Insecurity in the North

Introduction

The interconnection between nutrition, human health and the environment has been embedded in the knowledge systems and cultural practices of Indigenous Peoples for thousands of years. Country food hunted, fished, and gathered from the land is a pillar of Inuit health (ITK, 2014). However, dietary transition is very rapid and the rates of food insecurity are alarming, and both have important consequences for health and well-being in Arctic communities (Egeland et al., 2011). In Inuit Nunangat, 76% of Inuit aged 15 and over reported experiencing food insecurity (ITK, 2021). A disparity in access to water services has also been noted across the Arctic, contributing to water insecurity (Sohns et al., 2019). Access to safely managed drinking water services and nutritious food remains challenging for millions of people living in the circumpolar Arctic (Cassivi et al., 2023).

Country foods significantly contribute to the nutrition, health, and food security of Canadian Inuit communities (Gagné et al., 2012; Little et al., 2021). They represent important sources of protein, vitamins, and minerals (Allaire et al., 2021b). Despite this key role, the ongoing effects of colonization, climate change, changes in food preferences, socio-economic challenges and concerns about contaminant exposure lead to a rapid dietary transition in these communities and threaten their food security and sovereignty (Little et al., 2021). Time-honoured food hunting and harvesting practices are increasingly being replaced by diets consisting of store-bought, nutrient-poor market foods (Furgal et al., 2021). Unhealthy diets, embodied by a western diet that is high in saturated fats, sugar, and processed foods, is the leading modifiable risk factor associated with mortality and the second leading risk factor for disability in Canada (Bacon et al., 2019). As western dietary patterns become more prevalent in the Canadian Arctic, health concerns such as obesity, diabetes, and cardiometabolic disease are on the rise (Allaire et al., 2021a). Thus, the association between diet and disease becomes increasingly crucial to understand, especially for Inuit population.

Advances in technology have allowed for a more in-depth understanding of the tangible link between dietary practices and disease. Specifically, two complex and interconnected systems have been identified in the control of energy metabolism and in metabolic disorders (Iannotti & Di Marzo, 2021). The gut microbiome, an ecosystem of microorganisms dictated by environmental factors such as diet and drugs, plays a crucial role in many aspects of human health, including immunity, metabolism and behaviour (Valdes et al., 2018). The endocannabinoid system is comprised of cannabinoid receptors, endocannabinoids and the enzymes responsible for their synthesis and degradation (Lu & MacKie, 2016), together known as the endocannabinoidome. The endocannabinoidome plays a central role in regulating a large variety of processes, including metabolism, appetite and digestion, inflammation, and neuromodulation. Both systems are heavily influenced by diet and mediate many dietary implications for health including communication along the gut-brain axis.

Obesogenic high-fat diets enhance endocannabinoid levels, both in the brain and peripheral tissues (Forte et al., 2020), thus modulating gut-derived signal transduction to the brain through various biomolecules. These biomolecules impact energy regulation and are involved in the development of neuroinflammation, which can subsequently alter behaviours. Thus, dietary changes control the endocannabinoidome and its bidirectional relationships with the gut microbiome, which regulates not only gastrointestinal metabolism but also brain function (Choi et al., 2020b).

A deeper understanding of how gut microbiota respond to poor dietary conditions is possible through the advent of predictive tools and biomarkers. Rapid and efficient disease diagnosis within the medical field is challenging, especially in remote areas (Azzi, 2019). Current gut microbiota analysis is mainly based on sequencing technologies to determine microbial composition and gene expression. The development of new tools and model organisms to allow a more in-depth investigation of microbiome-derived molecules as well as identification of early molecular biomarkers that are relevant to cardiometabolic disease pathogenesis is vital (Anhê et al., 2019, 2018; Cornuault et al., 2022).

Remote northern communities also lack access to safely managed drinking water services, stemming from poor water quality and insufficient water quantities. Culturally appropriate health-based interventions are necessary to ensure inclusive water services and to achieve the Sustainable Development Goal (SDG) targets for universal access to water (Cassivi et al., 2023).

This chapter brings together results from Sentinel North program that are deepening our understanding of the positive impacts of country food on the intestinal microbiota. It also discusses the links between diet and chronic diseases and the implications at different levels, from food environments to the molecular level. Finally, it sheds light on culturally adapted initiatives that tackle food and water security issues in collaboration with Northern communities. Collectively, these advances can inform research and action to prevent disease development linked to diet, improve nutritional health and ensure inclusive water services.

KEY WORDS:

Traditional food, Western diet, Gut microbiome, Gut-brain axis, Metabolic health, Endocannabinoidome, Food environment, Water security

1. The Benefits of Omega-3

Selected research highlights

The traditional Inuit diet is rich in polyunsaturated fatty acids from the omega-3 family, particularly due to frequent fish consumption. The health benefits of omega-3 are increasingly recognized both for the general population and the Inuit.

1.1 In a population with non-pathological eating behaviours, a study found that plasma levels of an omega-3 derivative (2-monoacyl-glycerol) were positively associated with intuitive eating behaviours, i.e., eating behaviours based on physiological signals of hunger and satiety. Research is ongoing to better understand the involvement of these bioactive lipids in regulating eating behaviours and to develop new nutritional and pharmacological strategies (Rochefort et al., 2021).

1.2 The consumption of fish oil, a rich source of omega-3 polyunsaturated fatty acids, combined with cannabidiol (CBD) produced a significant anti-inflammatory effect in colitis mice models. Moreover, fish oil and CBD used separately or in combination affected the gut microbiota of mice. These results highlight the potential of using the combination of low doses of fish oil and CBD for treating inflammatory bowel diseases (Silvestri et al., 2020).

1.3 Using a human gut simulator, a research team demonstrated that consumption of omega-3-rich fish oil supplements can modulate the composition of microbiota based on the gut region. Furthermore, consumption of these supplements was associated with a remarkable blooming of *Akkermansia muciniphila*, a bacteria known for its health benefits (Roussel et al., 2022).

2. New Breakthroughs on Polyphenols

Selected research highlights

Polyphenols are abundant in Arctic berries frequently eaten by Nunavimmiut. Mounting evidence supports the beneficial potential of polyphenols against cardiovascular disease, particularly through their action on gut microbiota.

2.1 Specific classes of polyphenols, such as proanthocyanidins and ellagitannins, mitigate several aspects of metabolic syndrome, the collection of conditions that increase the risk of heart disease, stroke, and type 2 diabetes. There is growing evidence that gut microbiota is a key mediator of the health benefits of polyphenols (Anhê et al., 2019).

2.2 Polyphenolic extracts of cloudberry (*Rubus chamaemorus*), alpine bearberry (*Arctostaphylos alpina*) and lingonberry (*Vaccinium vitis-idaea*) all showed beneficial effects on insulin resistance, fasting and post-meal insulin levels in a murine model (Anhê et al., 2018). Consumption of specific Arctic berries could, therefore, reduce chronic inflammation related to obesity and metabolic disorders.

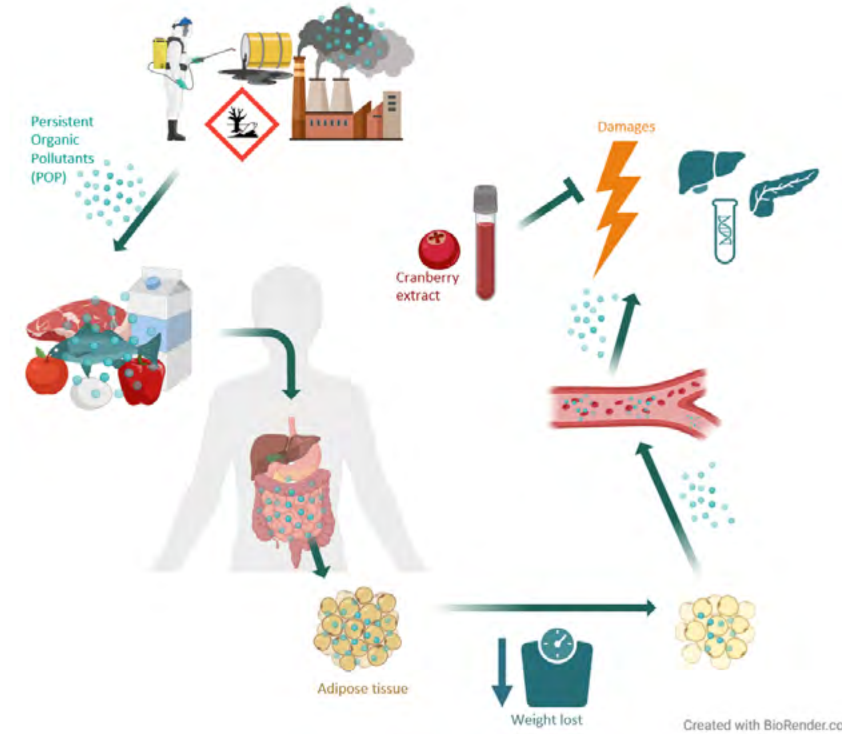
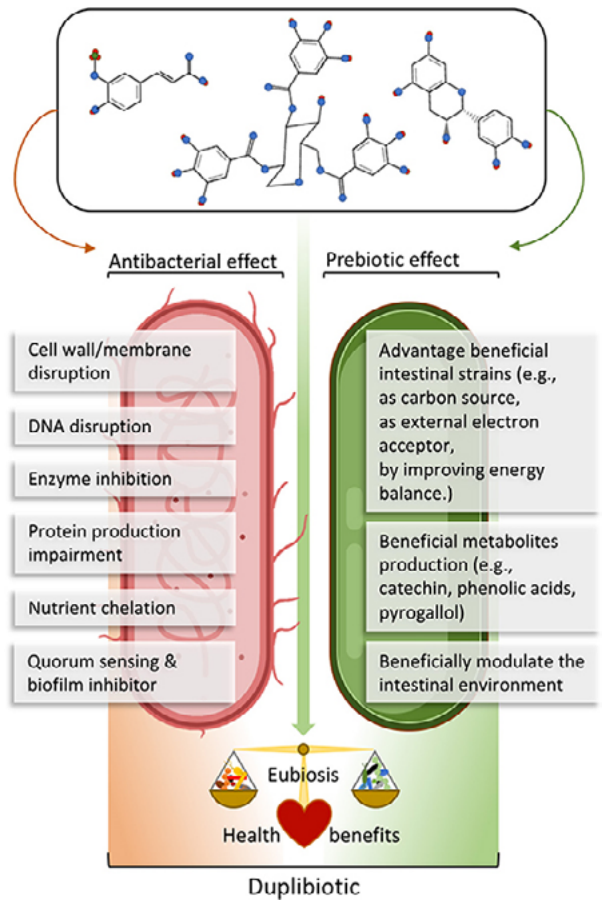


Figure 2.3
Representation of the impacts of persistent organic pollutants in the context of rapid weight loss. © Béatrice Choi

2.3 While weight loss induces the release of persistent organic pollutants (POPs) contained in adipose tissue and increases the pollutant levels in the body, the consumption of cranberry extracts used as a prebiotic decreased the load of these pollutants in mice models (Figure 2.3). These results are of interest to communities living in the Arctic who are particularly exposed to POPs through their diet (Choi et al., 2020a).

2.4 Polyphenols in blueberries reduced diet-related weight gain and improved insulin sensitivity. Specific classes of polyphenols in blueberries, including proanthocyanidins and anthocyanins, provided these beneficial effects on mice metabolic health, particularly through their action in modulating gut microbiota (Morissette et al., 2020).

Figure 2.5
Description of polyphenols direct antibacterial and prebiotic effects. Figure taken from Rodriguez-Daza et al., 2021, licensed under CC BY 4.0.



2.5 The term "duplibiotic" is proposed to describe polyphenols that modulate gut microbiota through their antibacterial and prebiotic action (Figure 2.5). The polyphenols' duplibiotic effect could help mitigate metabolic disturbances and intestinal dysbiosis. Therefore, polyphenols represent a target of interest in developing dietary strategies with therapeutic potential (Rodriguez-Daza et al., 2021).

Addressing Concerns about the Safe Consumption of Snow Geese

Snow geese are an important food resource for many Indigenous communities. The COVID-19 pandemic has raised concerns among some of these communities about the possibility of contracting the virus by eating these migratory birds. Because public health information at the time was not entirely conclusive, a research team obtained and analyzed samples from 500 geese and was able to conclude that these animals were not a vector for transmitting COVID-19. The results were quickly communicated, illustrating the ability of researchers to address the concerns of Indigenous communities (Frederick et al., 2021).

Infographics delivered to Indigenous communities and public health organizations in Canada. ©Alexandra Langwieder

3. Diet as a Determinant of Gut Microbiota

Selected research highlights

Diet is a major determinant of gut microbiota. Dietary changes can unbalance gut microbiota and result in cardiometabolic disorders. It is important to characterize gut microbiota, identify biomarkers and develop predictive tools for rapid and efficient diagnosis of cardiometabolic diseases.

3.1 In partnership with Nunavik collaborators, the taxonomic and functional characteristics of the gut microbiota of Nunavimmiut youths were identified from stool samples collected during the *Qanuilirpitaa?* 2017 survey. Results indicate that the Nunavimmiut gut microbiota exhibits high diversity and its composition is distinct from that of young adults from non-industrial and industrial societies (Figure 3.1). The Nunavimmiut diet, consisting of traditional and commercially produced foods, may explain their unique gut microbiota (Abed et al., 2022).

3.2 Progress has been made in the design of an optical sensor to detect key biomarkers produced by gut microbiota in real time. A model probe capable of real-time quantitative pH measurements *in vitro* has been designed. Preliminary experiments suggest that real-time pH measurements are also possible in the gut (Azzi, 2019).

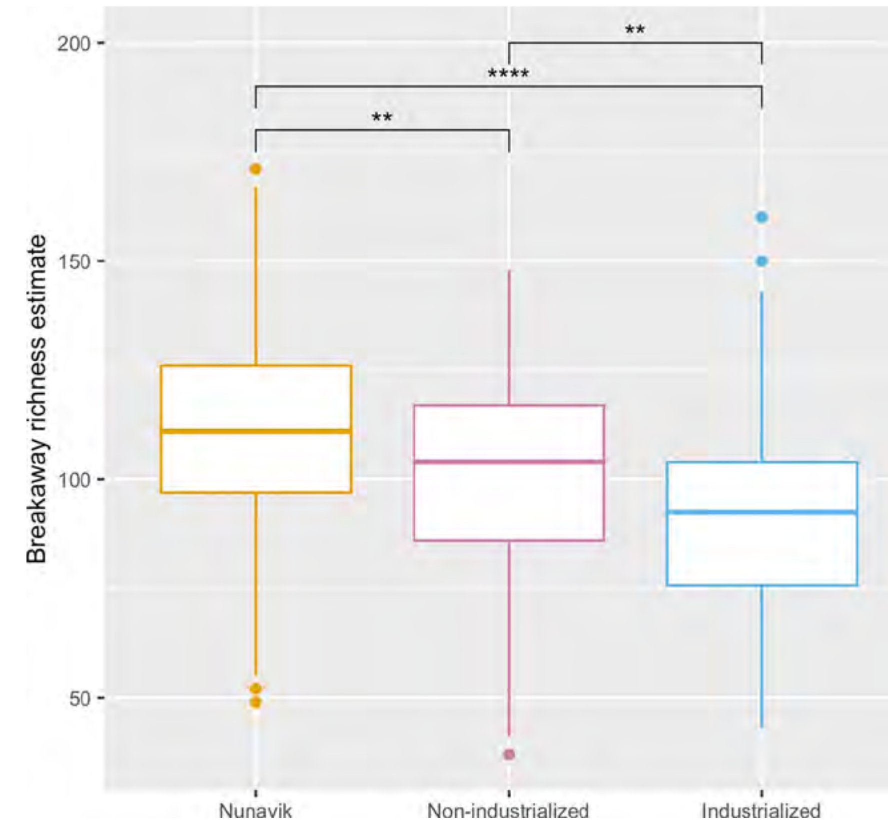
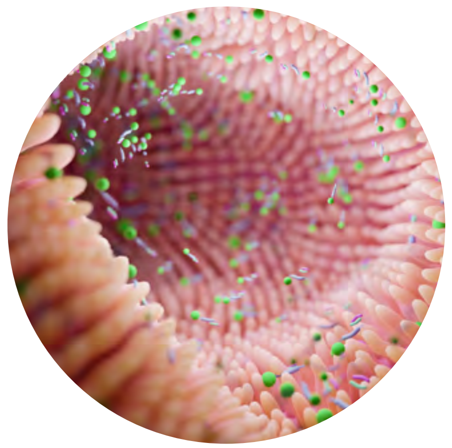


Figure 3.1
Intra-individual diversity of the gut microbiome in Nunavik Inuit is significantly higher than in non-industrial and industrial comparison groups using species-level relative abundance. The breakaway R package was used to estimate species richness. (*p-value ≤ 0.05, **p-value ≤ 0.01, ***p-value ≤ 0.001, ****p-value ≤ 0.0001). Figure taken from Abed et al., 2022, licensed under CC BY 4.0.

3.3 Bile acids have the potential to be used as biomarkers of gut microbiota. A convolutional neural network model was developed and successfully classified the five types of studied bile acids based on their spectra, even at low concentrations. The combined use of surface-enhanced Raman spectroscopy (SERS) and deep learning algorithms thus enabled the first detection and differentiation of bile acids (Lebrun et al., 2022).



4. The Gut-Brain Axis: Mechanisms of Action to be Further Investigated

Selected research highlights

An important bidirectional connection exists between the gut microbiota and the brain. However, the mechanisms involved in the regulation of brain functions by the gut microbiota are still poorly understood.

4.1 An obesogenic diet leads to neuroinflammation and an increase in blood-brain barrier permeability, which may impact the development of mood disorders. As a matter of fact, obesity is associated with an increased risk of developing a major depressive disorder. The gut microbiota is thus becoming a new therapeutic target to prevent and treat obesity-related comorbidities (Choi et al., 2020b).

"The gut-brain axis involves different pathways, including the microbiota and its metabolites. Several neurotransmitters and metabolites modulate immune system pathways that in turn influence behavior, memory, learning, locomotion, and mood and neurodegenerative disorders."

Adapted from Rutsch et al., 2020

4.2 The zebrafish (*Danio renio*) is becoming a promising animal model for better understanding the effects of gut microbiota on brain development. Several factors contribute to the relevance of this model, including its low cost, ability to evaluate large cohorts, the potential to obtain axenic larvae from non-axenic parents and availability of optical methodologies to probe larvae non-invasively by taking advantage of their transparency (Cornuault et al., 2022).

5. The Role of the Endocannabinoid System in Metabolic Health

Selected research highlights

The endocannabinoid system operates at the intersection between gut microbiota, gut-brain-axis communication and the host metabolism (Figure 5), playing a critical role in metabolic health and the development of obesity (Forte et al., 2020).

5.1 Poor dietary habits or obesity can disrupt the gut microbiome and the endocannabinoid system. Although the interactions between the gut microbiome and the endocannabinoid system remain to be defined, new nutritional or pharmacological approaches modulating these two systems could be beneficial for the treatment of metabolic syndrome or obesity (Iannotti and Di Marzo, 2021).

5.2 A study using axenic mice demonstrated the ability of gut microbiota to modulate the endocannabinoid system. Lacking a gut microbiome, these sterile mice showed profound alterations in the endocannabinoid system in the brain and gut, and particularly in the small intestine. These changes were reversed among adult male mice one week after a fecal microbiota transplant, which restored an active gut microbiome (Manca et al., 2020a; Manca et al., 2020b).

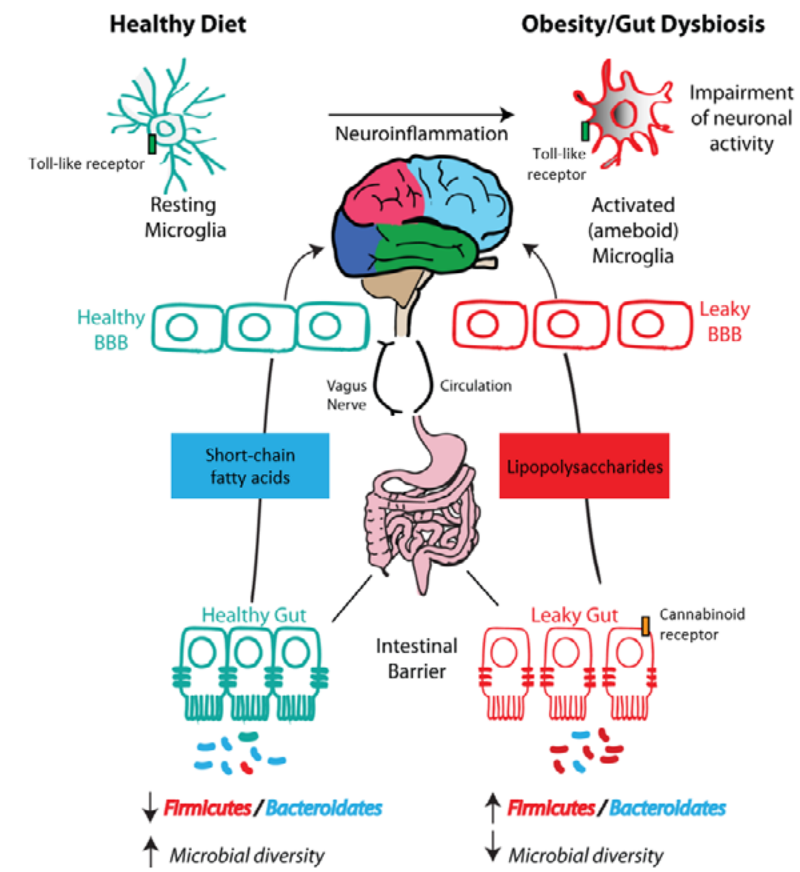


Figure 5
Interactions of healthy diet (green left side) and obesogenic diet (red right side) with gut microbiome–endocannabidoidome–brain axis. The diet influences gut microbiota composition and regulates intestinal permeability. Obesogenic diet leads to gut dysbiosis, inflammation, leaky intestinal and blood-brain-barrier (BBB). Figure taken from Forte et al., 2020, licensed under CC BY 4.0.

5.3 Gut microbiota and fatty acid intake determined endocannabinoid system (eCBome) signalling among a cohort of 195 individuals, independently of their body fat distribution. The study demonstrated that the intake of fatty acids was associated with levels of several eCBome mediators in plasma samples. Therefore, these results reveal the possibility of modulating plasma eCBome mediators with diet (Castonguay-Paradis et al., 2020).

5.4 A research team demonstrated that neurotransmitter signalling was altered among obese mice, resulting in dysfunction of adult hippocampal neurogenesis. These findings provide a molecular and functional mechanism to explain alterations in episodic memory in obese mice (Forte et al., 2021).

6. For New Food Systems

Selected research highlights

Traditional foods are integral to Inuit culture, nutrition, and health in the Arctic. However, food preferences have changed over the past few decades, with the majority of Nunavimmiut (68%) opting for a mixed diet comprising of both traditional foods and commercial products (Furgal et al., 2021).

6.1 From the Arctic to the South Pacific, the retail food sector in remote Indigenous communities shares common characteristics: high prices, low-quality foods, limited healthy food choices and increased availability of processed and unhealthy foods. This reality can result in a low nutritional value diet, exacerbating the already high levels of food insecurity in the Arctic and contributing to the development of chronic disease and obesity. Interventions are required to promote food sovereignty among Indigenous communities and develop healthy, affordable, and culturally appropriate food systems (Kenny et al., 2020).

6.2 Different dietary profiles strongly associated with socio-demographic characteristics were identified among Nunavik Inuit (Figure 6.2). The nutritional status, contaminant exposure and health issues of the different profiles will be studied to determine the possible solutions for adapted public health programs (Aker et al., 2022a).

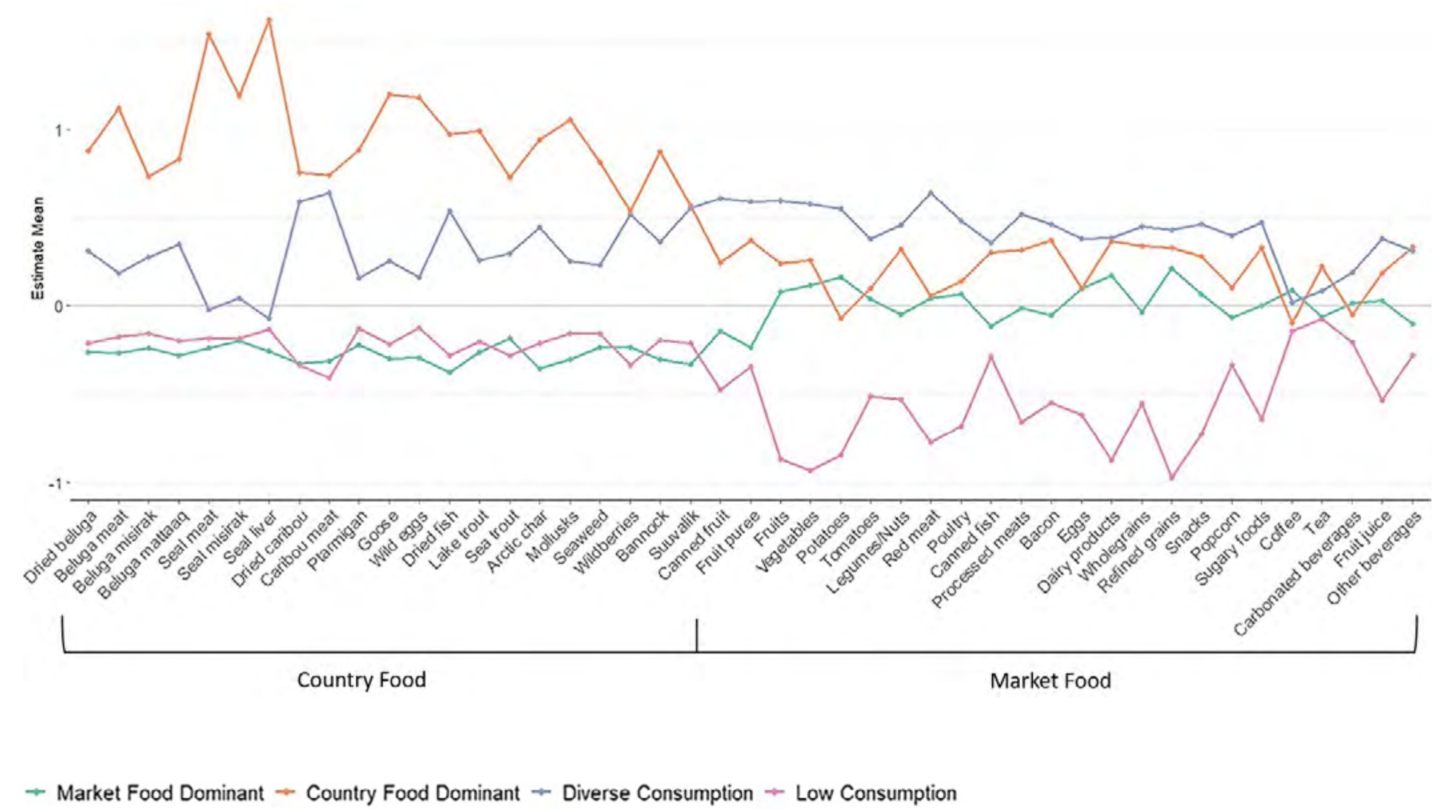


Figure 6.2
Four overall dietary profile have been identified: Market food-dominant profile included 42% of the study population. Women and Inuit adults aged 30–49 years were more likely to have this profile. Country food-dominant profile was the smallest group with 12,6% of the study population. Men, younger Inuit (aged 16–29 years), and older Inuit (≥ 50 years) were more often in this profile. Diverse consumption profile comprised 23,4% of the study population and included individuals who reported high consumption frequencies of both country and market food. Low consumption profile made up 21,9% of the study population and included individuals who reported high food insecurity. Figure adapted from Aker et al., 2022a, licensed under CC BY 4.0.

6.3 A research team is involved in a transdisciplinary participatory research initiative with the Nunavut community of Ikaluktutiak to implement a local food production system. To date, 16 outdoor mini-greenhouse prototype replicates have been installed to make outdoor agriculture possible in the High Arctic. Indoor hydroponic, aeroponic and soil-based systems have been implemented to support year-round farming. This research also enabled a recording of the knowledge associated with greenhouse practices and learning about the Ikaluktutiak inhabitants' perceptions of the nutritional quality of the fruits and vegetables available in grocery stores and their expectations concerning those grown locally (M. Dorais and C. Fournier-Côté, personal communication).

Pollutants in Commercial Foods

Canned foods, plastic-wrapped foods and many consumer goods may contain non-persistent chemicals. Exposure to these contaminants is receiving increasing attention in the Arctic, as an exploratory study conducted as part of the *Qanuilirpitaa?* 2017 survey suggests higher concentrations of some of these contaminants among the people in Nunavik compared with the general Canadian population. Women and Ungava Bay residents had the highest concentrations of these substances. Further studies are needed to confirm these findings, identify sources of exposure in the Arctic and investigate their effects on the health of Nunavik Inuit (Aker et al., 2022b).

7. Access to Quality Drinking Water

Selected research highlights

Many people living in the Arctic have limited access to drinking water. Remote Indigenous communities are particularly affected by this situation and face various challenges, including inadequate water quality and quantity, as well as intermittent supply service.

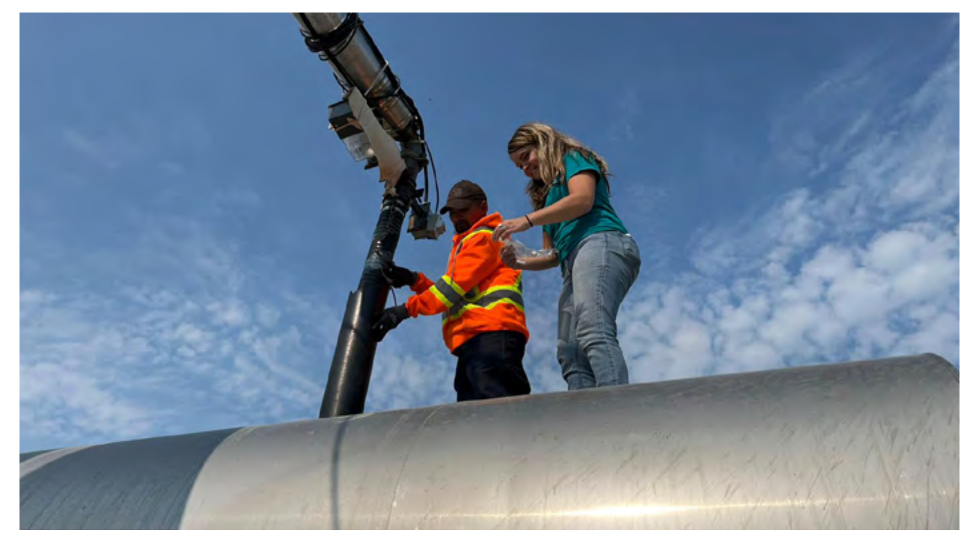
7.1 Culturally appropriate interventions that consider personal preferences on household risk perception and practices in accessing water are needed to improve and secure the drinking water supply for Arctic communities. Prevention of microbial and chemical contamination is the key to successful sanitation interventions from the water sources to the points of use (Cassivi et al., 2023).

7.2 A committee including researchers, Kativik Regional Government members, the Nunavik Regional Board of Health and Social Services and community representatives is working on drinking water issues. This collaboration enables the integration of local concerns and issues into research projects and ensures better knowledge transfer (S. Guilherme, personal communication).

7.3 A report on drinking water in Nunavik was produced in collaboration with the Makivik Corporation as part of the consultations for the creation of the Canada Water Agency. This report is based on a literature review and consultation with experts. The following issues were identified: (1) degradation of post-treatment water quality, (2) training of personnel for infrastructure use and maintenance, (3) protection of drinking water sources and (4) synergy between the different levels of government and water stakeholders (M. Rodriguez and D. Nadeau, personal communication).

7.4 To obtain a picture of the spatiotemporal variability of physicochemical and microbiological water quality, meteorological stations have been installed near drinking water sources and continuous monitoring of water quality from the source to the plant has been established in Kangiqsualujjuaq and Umiujaq, Nunavik. These efforts aim at determining protocols and decision-support tools for operators (M. Rodriguez, personal communication).

7.5 In Nunavik, a sampling program has shown that secondary disinfection by chlorination is not sufficient to ensure adequate protection during the domestic distribution and storage of drinking water. A decision support tool was developed in collaboration with the village of Kangiqsualujjuaq, Nunavik, to determine the appropriate amounts of chlorine to achieve disinfectant residuals that meet international standards while limiting the generation of potentially harmful disinfection by-products and chlorine tastes and odours that inhibit Nunavimmiut's consumption of tap water (Garcia-Sanchez, 2022).



Research Projects Cited in this Chapter

The knowledge and technological advances referenced in this chapter were generated by several Sentinel North interdisciplinary research teams. These scientific contributions were gathered from the projects listed below, which involved, in addition to the principal investigators, numerous researchers, graduate students, postdoctoral fellows, research professionals, collaborators, partners from northern organizations and national and international partners from the public and private sectors.

- Characterization and modelling of the key interrelationships of northern water systems under climatic, geosystemic, and societal pressures

  Principal Investigator: René Therrien (Dept. of Geology and Geological Engineering)

- Deciphering host-microbial interactions for cardiometabolic and mental health disorders with novel multimodal light-based sensing tools

  Principal Investigators: Denis Boudreau (Dept. of Chemistry), André Marette (Dept. of Medicine)

- NUNARISK: Early warning system for drinking water management and monitoring through the analysis of online and continuous environmental data

  Principal Investigators: Manuel J. Rodriguez (Graduate School of Land Management and Regional Planning), Daniel Nadeau (Dept. of Civil and Water Engineering)

- Optogenetics investigation of microbiota influence on brain development and epigenetics

  Principal Investigators: Paul De Koninck (Dept. of Biochemistry, Microbiology and Bio-informatics), Sylvain Moineau (Dept. of Biochemistry, Microbiology and Bio-informatics)

- Participatory action for an Inuit-led research on food production and nutrition in Inuit Nunangat

  Principal Investigators: Martine Dorais (Dept. of Phytology), Caroline Hervé (Dept. of Anthropology)

- The gut microbiome: Sentinel of the northern environment and Inuit mental health

  Principal Investigators: Richard Bélanger (Dept. of Pediatrics), Gina Muckle (School of Psychology)

- Sentinel North partnership research chair on ecosystemic approaches to health

  Chairholder: Mélanie Lemire (Dept. of Social and Preventive Medicine)

- Sentinel North research chair on the impact of animal migrations on Arctic ecosystems

  Chairholder: Pierre Legagneux (Dept. of Biology)

Research Projects Cited in this Chapter

Some results presented in this chapter are also drawn from research projects conducted by recipients of Sentinel North Excellence scholarship and postdoctoral fellowship awards.

- Sensor-in-fibre optical probes for molecules sensing in the gastro-intestinal tract of muridae models relevant to cardiometabolic diseases
  Victor Azzi (Master's Scholarship)
- Évaluation de la qualité de l'eau potable de la source au robinet au Nunavik
  Cristian Ruben Garcia Sanchez (Master's Scholarship)
- Impact de la modulation du microbiote sur l'excrétion de polluants organiques persistants lors d'une perte de poids
  Béatrice Choi (Ph.D. Scholarship)
- Synthèse de nanosondes luminescentes dans l'étude *in vivo* de marqueurs du microbiote intestinal
  Nicolas Fontaine (Ph.D. Scholarship)
- The association between per and polyfluoroalkyl substances (PFAS) and metabolic outcomes among Nunavimmiut adults
  Amira Aker (Postdoctoral Fellowship)
- Déterminants de la santé cardiométabolique et des habitudes alimentaires des Inuit du Nunavik en 2017
  Janie Allaire (Postdoctoral Fellowship)
- Approvisionnement en eau potable dans les communautés autochtones en région arctique : suivi et évaluation des risques sanitaires
  Alexandra Cassivi (Postdoctoral Fellowship)
- Utilisation des phages virulents pour contrôler le microbiote du poisson-zèbre
  Jeffrey Cornuault (Postdoctoral Fellowship)

Sentinel North has developed partnerships with leading international institutions to conduct innovative and interdisciplinary research projects. The following joint collaborative project has contributed to the results of this chapter.

- Joint International Research Unit for chemical and biomolecular research of the microbiome and its impacts on metabolic health and nutrition
  Director: Vincenzo Di Marzo (Dept. of Medicine)
  National Research Council, Italy
  Associated with the CERC in the microbiome-endocannabinoidome axis in metabolic health

Consiglio Nazionale delle Ricerche

Ongoing Sentinel North Research Projects

Several research projects supported by Sentinel North and through joint funding initiatives are ongoing as part of the second phase of the program (2021-2025). These projects, listed hereunder, continue to fill fundamental gaps in our scientific knowledge of the changing North.

- Development of resilient municipal wastewater treatment infrastructure targeting water reuse in Nunavik, Québec

  Principal Investigator: Céline Vaneeckhaute (Dept. of Chemical Engineering)

- Interactions between the northern environment and chronobiotics: Impact on cardiometabolic and neurometabolic health

  Principal Investigators: Alexandre Caron (Fac. of Pharmacy), Andréanne Michaud (School of Nutrition)

- Linking the marine environment and the nutritional quality of shellfish and beluga near Quaqtaq

  Principal Investigators: Mélanie Lemire (Dept. of Social and Preventive Medicine), Jean-Éric Tremblay (Dept. of Biology)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- NUNARISK: Early warning system for drinking water management and monitoring through the analysis of online and continuous environmental data

  Principal Investigators: Manuel J. Rodriguez (Graduate School of Land Management and Regional Planning), Daniel Nadeau (Dept. of Civil and Water Engineering)

- Participatory action for an Inuit-led research on food production and nutrition in Inuit Nunangat

  Principal Investigators: Martine Dorais (Dept. of Phytology), Caroline Hervé (Dept. of Anthropology)

- Sustainable and resilient country food systems for future generations of Nunavimmiut – Promoting food security while adapting to changing northern environments

  Principal Investigators: Frédéric Maps (Dept. of Biology), Tiff-Annie Kenny (Dept. of Social and Preventive Medicine)

- The exposome-microbiota-brain axis under the microscope to tackle environment-health interactions in the North

  Principal Investigators: Paul De Koninck (Dept. of Biochemistry, Microbiology and Bio-informatics), Pierre Ayotte (Dept. of Social and Preventive Medicine)

- TININNIMIUTAIT: Assessing the potential of local marine foods accessible from the shore to increase food security and sovereignty in Nunavik

  Principal Investigators: Lucie Beaulieu (Dept. of Food Sciences), Ladd Johnson (Dept. of Biology)

- Extreme zooming on intestinal permeability and the western-style diet: Unravelling the role of dietary antigens on the prevalence of cardiometabolic and mental health diseases in the North

  Principal Investigators: Flavie Lavoie-Cardinal (Dept. of Psychiatry and Neurosciences), Denis Boudreau (Dept. of Chemistry)

- Sentinel North partnership research chair on ecosystemic approaches to health

  Chairholder: Mélanie Lemire (Dept. of Social and Preventive Medicine)

- Sentinel North partnership research chair on the gut microbiome-endocannabinoid system as an integrator of extreme environmental influences on bioenergetics

  Chairholder: Cristoforo Silvestri (Dept. of Medicine)

- Joint International Research Unit for chemical and biomolecular research of the microbiome and its impacts on metabolic health and nutrition

  Director: Vincenzo Di Marzo (Dept. of Medicine)

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Open access (OA) means online and free access to research outputs.

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Figures License

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Acknowledgments
The following research team members contributed to the review of the scientific highlights presented in this chapter:

Jehane Abed, Denis Boudreau, Vincenzo Di Marzo, Charles-Félix Fournier-Côté, Stéphanie Guilherme, Tiff-Annie Kenny, Pierre Legagneux, Mélanie Lemire, Sylvain Moineau, Manuel Rodriguez and Cristoforo Silvestri.

We also thank Tiff-Annie Kenny for her comments on the introduction and Natalia Poliakova for her revision on the chapter.

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CHAPTER 5

Well-being: From Neurosciences to Sustainable Housing

From Stress Neurobiology to Sustainable Housing: Advancing Knowledge on Health and Well-being for the North

Introduction

Mental health and well-being are the critical basis by which humans can flourish, fulfil their potential, contribute to their communities, and remain resilient in the face of stress and adversity. However, according to the World Health Organization, about 970 million people were living with a mental disorder in 2019, making it one of the leading causes of disability worldwide (GBD 2019 Mental Disorders Collaborators, 2022; Lopez and Murray, 1998). In Canada, mental illness was estimated to affect more than 6.7 million people in 2011, or one in five Canadians (Smetanin et al., 2011). Mental health challenges are particularly pressing in Arctic and Subarctic regions, where rapid social and cultural changes impact the well-being of Indigenous populations (Young et al., 2012; Lehti et al., 2009). The National Representational Organization Inuit Tapiriit Kanatami has identified mental wellness as the number one health priority (Alianait Inuit-specific Mental Wellness Task Group, 2007), which was also reflected in the *Qanuilirpitaa?* 2017 health survey in Nunavik. Four out of ten Nunavimmiut reported experiencing clinically significant depressive symptoms (Muckle et al., 2020a), a level more than twice as high as the general Canadian population (Statistics Canada, 2020). Tackling this situation requires a holistic and culturally appropriate approach to mental health, recognizing that socio-economic factors such as housing play a role in determining health, including mental health and well-being (Alianait Inuit-specific Mental Wellness Task Group, 2007). Improving our capacity for diagnosis and treatment in multiple populations is also part of this approach, which brings together knowledge from diverse disciplines to provide new understanding of the biological roots of mental health problems, new early-detection methods, and new environmental and biological mechanisms that can be targeted for intervention (Patel et al., 2018).

Gradually, we are expanding our understanding of factors that underlie depression, including chronic stress (van Praag, 2004) and sex-based differences with respect to the prevalence, symptoms, and treatment of depression. For example, women are twice as likely to be diagnosed with major depressive disorder (MDD) compared to men (Dudek et al., 2021), a trend that was also observed within the Inuit Nunavik population where women reported distress more frequently than men (Muckle et al., 2020a; Kirmayer and Paul, 2007). Currently approved anti-depressant treatments have been estimated to be ineffective for 30 to 50% of patients from the general population (C. Ménard, personal communication). However, recent findings on the molecular mechanisms underlying mood disorders (Bittar et al., 2021; Mena and Labonté, 2019) and the interactions of the neurovascular and neuroimmune systems (Dudek et al., 2020; Dion-Albert et al., 2022a) may point toward innovative treatments and earlier diagnosis. Fundamental research in brain structure (Allard and Serrano, 2020; Zheng et al., 2020), new optogenetic technology using animal models (Gagnon-Turcotte et al., 2020), and biomarker identification (Gagné et al., 2020; Arsenault et al., 2021) are expanding our knowledge, and translating results into potential diagnosis and therapeutic advances. Developing biomarkers capable of diagnosing diseases in the early stages would be of paramount importance to tackle mental health issues.

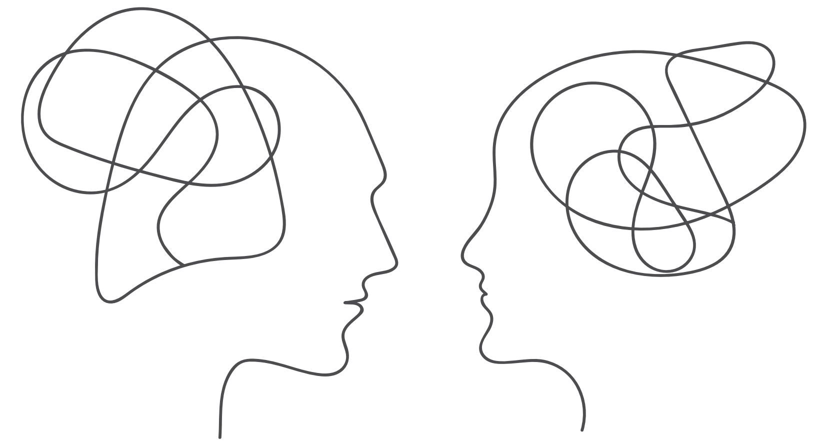
The complex web of environmental, sociocultural, and physiological factors that determine mental health requires an "ecosystem approach" that involves multiple community stakeholders in fostering mental wellness (Paquin et al., 2020). Within this holistic understanding of mental wellness, access to housing plays a major role. In 2016, over half of Inuit living in the north were in crowded housing (ITK, 2019), an issue that seems to be linked with mental distress in northern communities (Pepin et al., 2018; Perreault et al., 2022). Not only do northern communities lack housing stock, but what is available may be of lower quality. Since this housing crisis is unfolding within a unique northern context, solutions will require designing and building culturally and environmentally appropriate housing (Bayle, 2020; Vachon, 2020). Collaboration between architects and community stakeholders has led to the development of tools for sustainable planning of northern villages. "Biophilic design," which seeks to integrate the human-built environment into the natural environment (Kellert et al., 2011), appears to be a promising approach to address the biological and psychological need for natural light in high latitude environments (Parsaee et al., 2019, 2020, 2021).

The links between housing and public health are multifaceted, and intersect not only with mental health, but also respiratory illnesses and their risk factors. Inuit children are disproportionately affected by respiratory infections. Causes for the high rates of infections include poverty, overcrowding, and housing in need of major repairs and a better ventilation (Kovesi, 2012). Tobacco use compounds these ill effects on respiratory health and is particularly significant for northerners, for whom rates of smoking are higher than the national average (Bélanger et al., 2020).

This chapter gathers Sentinel North research results from a broad range of disciplines. Together, these results contribute to addressing mental health issues and well-being in northern communities. From neuroscience to architecture, these interdisciplinary insights aim to improve our understanding of mental health problems, identify new biomarkers for early diagnosis and treatment, encourage an ecosystem approach to mental health, and prevent health problems through culturally sensitive interventions that address key health determinants, such as housing.

KEYWORDS:

Well-being, Mental Health, Neuroscience, Stress, Resilience, Housing Planning, Air Quality, Health Determinants, Action-Research, Nordic Architecture, Biophilia



1. The Effects of Stress on Mental Health

Selected research highlights

The *Qanuilirpitaa*? 2017 health survey reveals that most Nunavimmiut have experienced stressful social and historical events with a potentially negative impact on their lives (Muckle et al., 2020b). These events may be associated with chronic stress, that is a prolonged and repeated exposure to stress, which can lead to the appearance or progression of mental health issues. To enhance the efficacy of proposed treatments, it is essential to gain a comprehensive understanding of the effects of chronic stress, as well as of the molecular and functional mechanisms underlying its impact, on both men and women.

1.1 Sexual dimorphism observed in major depressive disorder appears to come from sex-specific molecular alterations affecting the functional pathways that allow us to cope with daily life stress. Transcriptional changes associated with epigenetic alterations have been observed in the brains of men and women suffering from depression. Similar changes have been reported in animal models of depressive-like behaviours induced by stress (Mena and Labonté, 2019).

1.2 In mice, prolonged exposure to stress leads to changes in the mesocortical and mesolimbic dopaminergic pathways, which play an important role in the expression of depressive-like behaviors. In addition, differences in the molecular and morphological alterations have been noted between animals of the opposite sexes, which would explain the differences observed in clinical manifestations of mood disorders within men and women (Quessy et al., 2021).

1.3 The medial prefrontal cortex is a region of the brain that is involved in responses to stress. Depressive behaviours induced by chronic exposure to stress in male and female mice result from specific changes in the pathways that control morphological and synaptic properties of transcriptional activity in the prefrontal cortex. The nature of the changes differs between males and females (Bittar et al., 2021).

1.4 Some mechanisms linked to inflammation could promote the loss of blood-brain barrier integrity involved in different mental disorders, especially in major depressive disorder, bipolar disorder, and schizophrenia. Furthermore, sex hormones modulate neurovascular integrity by regulating neuroinflammation and directly affecting astrocyte and endothelial cell functions. Alterations to cerebral blood flow and sex-specific transcriptional pathways may be the key to discovering new markers for mental illnesses as well as promising diagnostic tools (Dion-Albert et al., 2022a).

2. Understanding Resilience to Stress

Selected research highlights

Following the experience of chronic stress or a traumatic event, certain individuals do not develop any physical, psychological, or behavioural changes; they remain resilient to adversity. Resilience is thus defined as the capacity to resist or recover quickly when faced with difficult conditions (Smith et al., 2008).

2.1 The blood-brain barrier (BBB) constitutes the last border between the brain and harmful toxins or inflammatory signals circulating in the blood. Chronic stress alters this barrier's integrity, which can lead to depressive behaviours. Molecular changes in the BBB associated with resilience to stress have been identified and may play a protective role for the neurovascular system (Figure 2.1). These results highlight the importance of studying neurovascular pathologies brought on by stress in order to identify new therapeutic targets so as to treat mood disorders and foster resilience (Dudek et al., 2020).

2.2 Epigenetic changes, such as histone acetylation/methylation and DNA methylation, take part in stress response. Epigenetic modification of the genes involved in synaptic plasticity and the endocrine, immune, and vascular systems are linked to resilience. Identifying central and peripheral epigenetic changes that foster resilience to stress represent promising novel targets in the development of preventive and personalized medicine (Dudek et al., 2021).

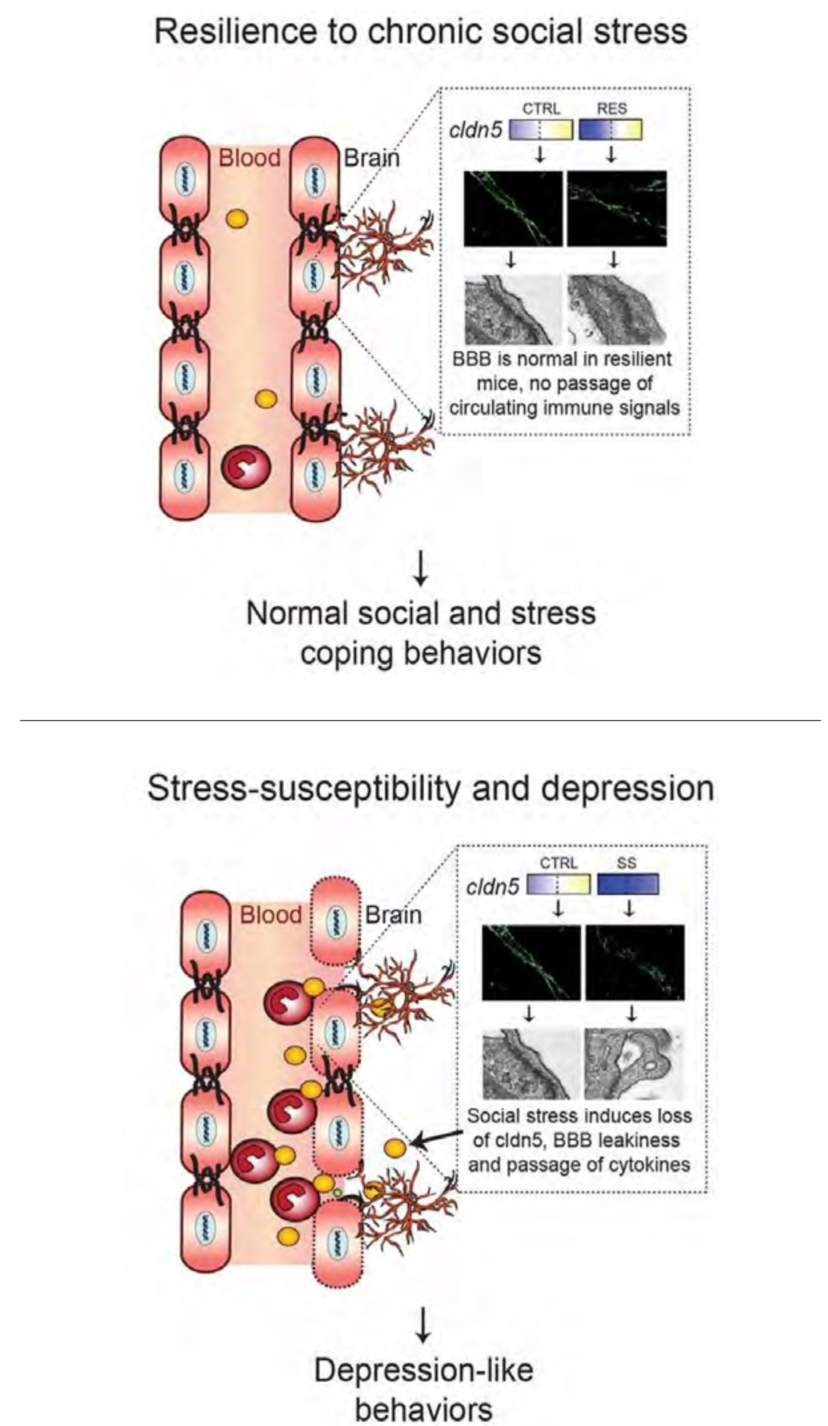


Figure 2.1
Claudin5 (cldn5) is a protein responsible for tight junctions of the blood-brain barrier (BBB). Claudin5 permissive epigenetic regulation is associated with maintenance of BBB integrity and stress resilience while lack of endothelial molecular adaptations and inflammation leads to cldn5 loss, BBB leakiness and depression-like behaviors. Figure taken from Dudek et al., 2020, licensed under CC BY 4.0.

3. Toward Early Diagnosis of the Main Psychiatric Disorders

Selected research highlights

Major depressive disorder is the most common consequence of chronic stress and a major cause of disability in the world (Vos et al., 2020). However, depression is diagnosed solely on the basis of self-reported symptoms. It is important to develop reliable biomarkers in order to identify individuals at risk of developing the illness and to ensure more rapid, effective, and appropriate management.

3.1 Chronic stress alters the blood-brain barrier (BBB) at different places depending on sex. In the female mouse, stress alters the BBB of the prefrontal cortex (Figure 3.1), which causes anxiety- and depressive-like behaviours. In the event of chronic stress, these females presented changes in soluble E-selectin levels. In humans, the same changes in circulating soluble E-selectin, BBB gene expression, and morphology were observed in blood serum and postmortem brain samples from women diagnosed with major depressive disorder (MDD). Soluble E-selectin in circulation may therefore be a biomarker of interest in diagnosing MDD in women (Dion-Albert et al., 2022b).

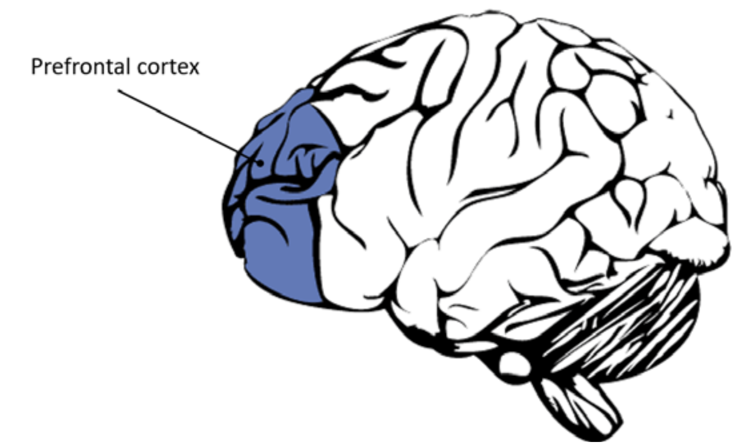


Figure 3.1
Prefrontal cortex of the brain. Figure modified from Erik Lundström, licensed under CC BY-SA 3.0.

3.2 The retina can be used to detect psychiatric disorders since it is part of the central nervous system, and both share the same embryonic origin. The electroretinogram (ERG) is a signal generated by the retina in response to a flash of light and represents a non-invasive and reliable approach. In mouse models, the ERG was shown to predict the expression of susceptibility and resilience before stress exposition in males and females with up to 71% efficacy (Figure 3.2; Arsenault et al., 2021).

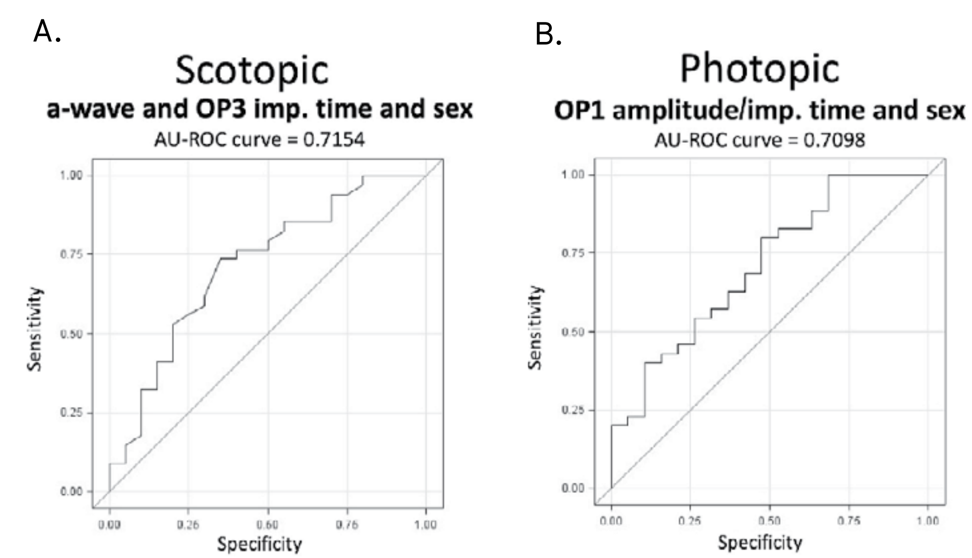


Figure 3.2
Electroretinogram can predict the expression of stress susceptibility and resilience in mice. (A) The scotopic model (associated to rods) has an area under the receiver operating characteristic (AU-ROC) curve of 0.7154 ($p < 0.05$) and (B) the photopic model (associated with cones) has an AU-ROC curve of 0.7098 ($p < 0.05$). Figure taken from Arsenault et al., 2021, licensed under CC BY 4.0.

3.3 Children with a high genetic risk of developing schizophrenia, bipolar disorder, or major depressive disorder presented an abnormal response in their cones and rods during the electroretinogram (ERG) test, similar to what has been reported in adult patients with these conditions. These results suggest that some features of the ERG as a risk endophenotype could be used in defining a childhood risk syndrome (Gagné et al., 2020).

3.4 Preliminary data have revealed that children at risk of developing one of the major psychiatric disorders show some difficulties with regard to intermodal transfer, that is, the transfer of sensory information from one sense to another. In these same children, difficulties in multisensory integration and emotional body processing have also been observed. Further work is needed to determine whether these results can lead to the identification of new risk biomarkers or endophenotypes (P. Marquet, personal communication).

3.5 Close analysis of fibroblasts from patients with bipolar disorder has led to the identification of a promising cell-specific biomarker that could serve as an aid in early diagnosis. These observations were made using quantitative phase microscopy based on digital holographic microscopy, a non-invasive technique. Validation studies of a companion diagnostic test with a view to making it available commercially are underway (P. Marquet, personal communication).

4. Some Tools for a Better Understanding of the Brain

Selected research highlights

To better understand how the brain works, several approaches have been developed. Whether it be through the optimization of the zebrafish animal model or the use of optogenetics or network science, knowledge is evolving to allow for possible new therapeutic approaches.

4.1 To understand how some exposures that individuals experience during embryonic development affect mental health, research teams have used the zebrafish animal model. Its transparency in the larval stage makes it possible to observe, with the help of advanced neurophotonic and optogenetic technology, the activity of all the neurons in the fish's brain. This model will thus allow researchers to study the effects of environmental factors on fundamental processes of brain function, such as sensory integration, behaviour, and learning (P. De Koninck, personal communication).

4.2 A multichannel optogenetic system capable of operating in a closed loop was designed to monitor neural activity in mice. This system works with optogenetics, a technology that uses light to selectively activate neurons in genetically modified animals to observe the effect on large biological networks. This work speeds up the development of new therapeutic approaches to brain diseases (Gagnon-Turcotte et al., 2020).

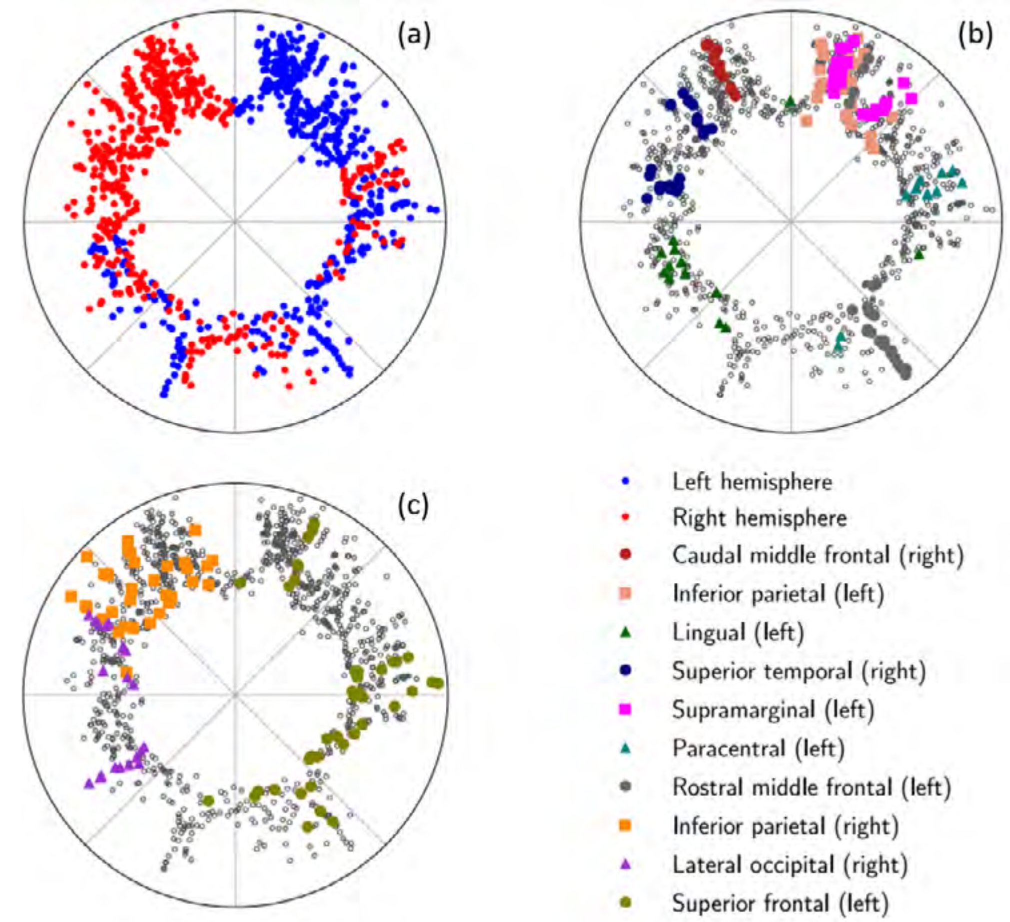


Figure 4.3
(a) Hyperbolic map obtained for the Human5 connetome. Nodes belonging to the two different hemispheres are shown in blue and red. (b) and (c) A sample of representative neuroanatomical regions are superimposed over the inferred positions of nodes shown on (a). Most neuroanatomical regions of Human5 are localized in narrow regions of the similarity space in the hyperbolic maps. Figure modified from Allard and Serrano, 2020, licensed under CC BY 4.0.

4.3 Models of networks immersed in hyperbolic spaces have made it possible to represent the structure of the connectome, the set of neuronal connections, almost perfectly (Figure 4.3). Thus, human connectomes, as well as those of various species, have been represented. This work offers a new perspective to map the organization of various regions of the brain (Allard and Serrano, 2020).

4.4 A renormalization semi-group defined based on networks immersed in a hyperbolic space was used to reproduce the multiscale properties of human connectomes. The results support that the same principles govern brain connectivity at different scales and lead to efficient decentralization. The impact of this work enables the development of advanced tools to simplify digital reconstruction and simulation of the brain (Zheng et al., 2020).

5. Developing an Ecosystemic Approach to Mental Health

Selected research highlights

Mental health and well-being require a holistic view and a comprehensive approach, whereby communities and organizations work together to address these issues. Many determinants of health, including sociocultural and environmental factors, influence mental health and need to be considered in this approach, particularly in northern communities.

5.1 An ecosystemic approach allows for the interactions between sociocultural, ecological, and biological factors of health to be considered. Since the risks of developing schizophrenia are multi-factorial and interdependent, an ecosystemic approach is needed; an approach that integrates different bodies of knowledge and involves the communities concerned (Paquin et al., 2020).

5.2 A research team analyzed the associations between different sociocultural factors and mental health among the Inuit of Nunavik. The results showed that stronger family cohesion and a regular practice of hunting and fishing were associated with lower depression scores. These sociocultural factors therefore deserve more attention in the areas of prevention and mental health promotion programs for Inuit (Poliakova et al., 2022).

5.3 The well-being and mental health of northern Indigenous communities are closely linked to a connection to the land. The extent of climate change in Arctic and subarctic regions is limiting access to the land and affecting livelihoods. Changes related to loss of identity and culture, food insecurity, interpersonal stress and conflicts, and housing problems also have an impact on mental health (Figure 5.3). Health clinicians can play a role in recognizing and offering support to those affected by these disruptions (Lebel et al., 2022).

Figure 5.3
The mental health-related impacts of environmental changes in the circumpolar North. Figure modified from Lebel et al., 2022, licensed under CC BY 4.0. Figure created with BioRender.

5.4 A new model combining genetic and socioeconomic risk factors improves the capacity to predict the development of psychiatric disorders, such as schizophrenia and bipolar disorder. In particular, the results indicate that an increase in the Blishen index (a rating scale that measures socioeconomic status) of one unit is associated with a reduced risk of developing these same disorders (Bahda, 2022).

A more inclusive approach to brain research

Sentinel North neuroscience researchers have embarked on a multicultural approach with Indigenous communities as part of the Canadian Brain Research Strategy. The goal of this initiative is to further research on the central nervous system in a way that better reflects the diversity of the Canadian population. The research will be able to incorporate Indigenous knowledge and thus better meet the needs of these populations (Perreault et al., 2023).

6. Revisiting the Planning and Design of Housing for the Well-Being of Northern Populations

Selected research highlights

Access to sustainable and culturally appropriate housing promotes better physical and mental health. There is a need to work with and build the capacity of local communities to develop and facilitate access to such housing.

6.1 A decision-making support tool has been developed to support sustainable and resilient planning in Nunavik's villages. Using a multidisciplinary approach and in collaboration with the community of Kangiqsualujjuaq, the project identified planning principles tailored to local Inuit aspirations. One of the principles is to contribute to the community's well-being, notably by ensuring that the architecture of houses and community buildings supports physical and psychological health. The tool is available online: Pinasuqatigiitsuta.org.

6.2 The complexity of the processes related to producing housing in Nunavik encourages a logic based on "building" and a technical rationale rather than on a perspective considering the "dwelling" of the North, including social, cultural, and symbolic considerations. Linking and integrating the ways of building and residing in buildings by working together with local stakeholders could allow for the creation of housing that is better rooted in the realities and aspirations of Inuit communities and Inuit ways of living (Vachon, 2020).

Figure 6.3
The definition of home is presented according to three main themes that are most present in the literature studied: 1) the home-land (harmony between place and home); 2) the home-subject (a body that protects gestures and bodies); and 3) the home-family (the social space and the space to talk). © Myrtille Bayle

6.3 A review of the literature has allowed us to better understand the Inuit perspective of the home. The symbolic Inuit home is defined as a protective body, a space of refuge, and a supportive place for transmitting culture (Figure 6.3). In order for the built environment to reflect the concerns and vision of the Inuit world, it is important to encourage the integration of the Inuit inhabitant in the production of his dwelling (Bayle, 2020).

A much-needed evaluation of practices in partnership research projects in an Indigenous context

A conceptual modelling of collaborative research revealed the stakeholders involved and identified the factors that determine the authenticity of research partnerships between universities and Indigenous communities. Factors include the quality of the relationship between the partners, the level of trust in stakeholders and the organizations they represent, the duration of the partnership, and a suitable mediation process to establish shared goals and objectives. This model provides a better understanding of the processes that determine the success of research with Indigenous communities (Gouin, 2020).

7. A Nature-Based Architectural Approach for the Well-Being of Inhabitants

Selected research highlights

With limited availability of natural light and a unique photoperiod, Arctic and subarctic regions present challenges for architectural design. One of the goals of the biophilic approach is to integrate natural light into architectural design strategies to improve the quality and habitability of interior spaces while increasing their relationship with the outdoors. This approach, culturally adapted to local populations, can thus contribute to the health and well-being of inhabitants.

7.1 A digital tool was designed to visualize the qualitative and quantitative aspects of light using HDR (High Dynamic Range) images. These images create luminance maps, accurately render human perception, and generate photopic/melanopic dominance maps. The resulting spatial representations allow for improved communication between architects and other building stakeholders and promote better integration of daylight into future architectural projects (Lalande et al., 2020).

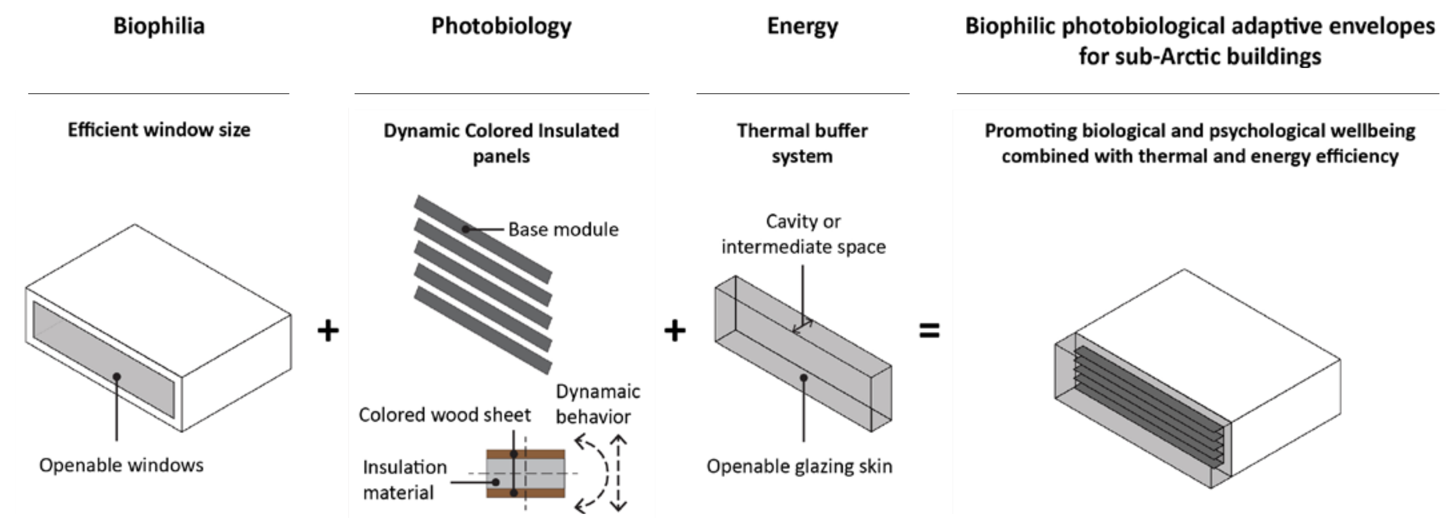


Figure 7.2
The biophilic-photobiological adaptive envelope model for subarctic buildings including essential components and configurations.
Figure taken from Parsaee, 2021.

7.2 For people living in northern territories, biophilic design must be adapted to extremely cold climates in order to meet their needs. A fundamental multi-skin adaptive envelope model (Figure 7.2) based on key biophilic and photobiological indicators for subarctic buildings was developed to enable efficient indoor-outdoor connections (Parsaee et al., 2019; Parsaee et al., 2020; Parsaee et al., 2021).

7.3 An action-research project led by professors in architecture, and carried out in partnership with the community of Ikaluktutiak, Nunavut, integrated bioclimatic concepts aimed at food self-sufficiency and health of occupants, while taking into account traditional knowledge. The objective was to design low-energy buildings that could withstand the harsh climate conditions of the region. As part of this research, several projects by professional master's students were awarded prizes in *the American Institute of Architects Committee on the Environment competition* (C. Demers, personal communication).

8. The Role of Ventilation in Indoor Air Quality

Selected research highlights

Between 2007 and 2012, hospitalization rate related to respiratory system diseases in children under one year of age was nearly 7 times higher in Nunavik than for the whole province of Quebec (NRHBSS and INSPQ, 2015). Several factors influence respiratory health, including indoor air quality and home ventilation systems.

8.1 In Nunavik, interventions performed on ventilation systems led to a decrease in respiratory infections and an improvement in indoor air quality. These results suggest that proper use and maintenance of residential ventilation systems may contribute to a reduction in respiratory infections among Nunavimmiut children. That said, children's respiratory health is the result of a combination of multiple factors. Thus, collaborative work between local health and housing authorities is essential to reduce the health inequities affecting northern communities (Poulin et al., 2022).

8.2 The effects of three different ventilation systems and their optimization on microbial communities in bioaerosols and dusts were studied in 54 newly constructed or renovated dwellings in Nunavik. The type of ventilation and its optimization had no effect on microbial communities, which were probably more affected by human activities, the main source of biological particles in the study (Degois et al., 2021).

9. A Smoke-Free Indoor Environment for the Health of Residents

Selected research highlights

Smoking and exposure to second-hand smoke are prevalent in Nunavik. The *Qanuilirpitaa*? 2017 health survey revealed that a significant proportion of Nunavimmiut aged 16 years and older are smokers (Bélanger et al., 2020). It is important to deal with this public health issue.

9.1 Levels of benzene, toluene, and polycyclic aromatic hydrocarbons (PAHs) were significantly higher in Inuit adults than in adults in Canada or the United States. The results suggest that the high prevalence of smoking in Nunavik is an important source of exposure to benzene and PAHs. This reinforces the importance of regional efforts to reduce smoking and encourage a smoke-free indoor environment in Nunavik homes. Inquiries should also be conducted to determine other possible sources of exposure (Caron-Beaudoin et al., 2022).

9.2 Work has shown that during exposure to cigarette smoke, inflammation is marked by a rapid and sustained infiltration of IL-1 neutrophils and the release of pulmonary surfactant and the alteration of its homeostasis. In mice, results have shown that neutrophils play a crucial role in maintaining lung homeostasis during acute exposure to cigarette smoke (Milad et al., 2021).

9.3 Electronic cigarette vapours, without nicotine or flavour, can be harmful and influence the lungs' response to tobacco cigarette smoke exposure in mice model who use both, potentially altering the pathological course of smoking. This dual exposure leads to an increase in airway resistance (Lechasseur et al., 2020).

Research Projects Cited in this Chapter

The knowledge and technological advances referenced in this chapter were generated by several Sentinel North interdisciplinary research teams. These scientific contributions were gathered from the projects listed below, which involved, in addition to the principal investigators, numerous researchers, graduate students, postdoctoral fellows, research professionals, collaborators, partners from northern organizations and national and international partners from the public and private sectors.

- Biological signatures of stress responses and potentiality of a diet enriched in n-3 fatty acids to promote positive mental health status despite adversity

  Principal Investigator: Caroline Ménard (Dept. of Psychiatry and Neurosciences)
- Development, implementation and use of miniature portable technologies for the prevention, assessment and treatment of chronic diseases in northern areas

  Principal Investigator: Laurent Bouyer (Dept. of Rehabilitation)
- Doing things differently: An atlas of best practices and opportunities for culturally acceptable and sustainable living environments in Nunavik

  Principal Investigators: Geneviève Vachon (School of Architecture), Michel Allard (Dept. of Geography)
- Impact of environmental conditions on airway microbiota and respiratory health in the North

  Principal Investigators: François Maltais (Dept. of Medicine), Marc Ouellette (Dept. of Microbiology, Infectious Disease and Immunology)
- Optimizing biophilia in extreme climates through architecture

  Principal Investigators: Claude Demers (School of Architecture), Marc Hébert (Dept. of Ophtalmology and ORL-Head and Neck Surgery)
- The use of diatom microalgae for improving the treatment of the light-driven dysfunctions of the biological clock in Arctic human populations

  Principal Investigator: Johann Lavaud (Dept. of Biology)
- Sentinel North partnership research chair in economics and brain health

  Chairholder: Maripier Isabelle (Dept. of Economics)
- Sentinel North partnership research chair in molecular neurobiology of mood disorders

  Chairholder: Benoît Labonté (Dept. of Psychiatry and Neurosciences)
- Sentinel North research chair in the neurobiology of stress and resilience

  Chairholder: Caroline Ménard (Dept. of Psychiatry and Neurosciences)
- Sentinel North partnership research chair on ecosystemic approaches to health

  Chairholder: Mélanie Lemire (Dept. of Social and Preventive Medicine)
- Sentinel North research chair on the applications and theory of network analysis

  Chairholder: Antoine Allard (Dept. of Physics, Physical Engineering, and Optics)
- Sentinel North research chair on the relations with Inuit societies

  Chairholder: Caroline Hervé (Dept. of Anthropology)

Research projects cited in this chapter

Some results presented in this chapter are also drawn from research projects conducted by recipients of Sentinel North Excellence scholarship and postdoctoral fellowship awards.

- Repenser le rôle de l'habitant dans le logement social au Nunavik: vers une intégration des valeurs Inuit
  Myrtille Bayle (M. Sc. Scholarship)
- Effets d'une exposition prénatale et postnatale aux contaminants et nutriments issues d'une alimentation traditionnelle Inuit sur le développement cognitif d'enfant d'âge scolaire
  Mireille Desrochers-Couture (Ph.D. Scholarship)
- Les processus de réalisation des projets d'habitations au Nunavik: vers une conception inclusive des acteurs locaux
  Marika Vachon (Ph.D. Scholarship)
- Recherche partenariale en aménagement dans les milieux nordiques: évaluation des processus participatifs en contexte innu
  Élisa Gouin (Ph.D. Scholarship)
- Role of the endocannabinoid system in stress resilience and depression: A master regulator of neurovascular and gut health
  Katarzyna Anna Dudek (Ph.D. Scholarship)
- Amélioration de la qualité de l'air intérieur dans les habitations du Nunavik: projet d'optimisation de la ventilation
  Jodelle Degois (Postdoctoral Fellowship)
- Role of blood-brain barrier transport in depression
  Fernanda Neutzling-Kaufmann (Postdoctoral Fellowship)

Sentinel North has developed partnerships with leading international institutions to conduct innovative and interdisciplinary research projects. The following joint collaborative project has contributed to the results of this chapter.

- Joint International Research Unit in child neural development and psychiatry
  Director: Pierre Marquet (Dept. of Psychiatry and Neurosciences)
  University of Lausanne, Switzerland
  Associated with the CERC in Neurophotonics

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Ongoing Sentinel North Research Projects

Several research projects supported by Sentinel North and through joint funding initiatives are ongoing as part of the second phase of the program (2021-2025). These projects, listed hereunder, continue to fill fundamental gaps in our scientific knowledge of the changing North.

- Biological signatures of stress responses and potentiality of a diet enriched in n-3 fatty acids to promote positive mental health status despite adversity

  Principal Investigator: Caroline Ménard (Dept. of Psychiatry and Neurosciences)

- Biophilic design in the Arctic: Immersive community co-creation to reconcile well-being and energy performance in Ikaluktutiak architecture

  Principal Investigators: Claude Demers (School of Architecture), Marc Hébert (Dept. of Ophthalmology and ORL-Head and Neck Surgery), Jean-François Lalonde (Dept. of Electric and Computer Engineering)

- Extreme zooming on intestinal permeability and the western-style diet: Unravelling the role of dietary antigens on the prevalence of cardiometabolic and mental health diseases in the North

  Principal Investigators: Flavie Lavoie-Cardinal (Dept. of Psychiatry and Neurosciences), Denis Boudreau (Dept. of Chemistry)

- Housing and energy transition in Nunavik: A better understanding of human, technical and environmental issues

  Principal Investigator: Louis Gosselin (Dept. Of Mechanical Engineering)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Technical-social solutions to expand the use of renewable energy from Whapmagoostui-Kuujjuarapik to other regions of Nunavik

  Principal Investigator: Jasmin Raymond (INRS)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- The exposome-microbiota-brain axis under the microscope to tackle environment-health interactions in the North

  Principal Investigators: Paul De Koninck (Dept. of Biochemistry, Microbiology and Bio-informatics), Pierre Ayotte (Dept. of Social and Preventive Medicine)

- Sentinel North partnership research chair in economics and brain health

  Chairholder: Maripier Isabelle (Dept. of Economics)

- Sentinel North partnership research chair in molecular neurobiology of mood disorders

  Chairholder: Benoît Labonté (Dept. of Psychiatry and Neurosciences)

- Sentinel North partnership research chair on ecosystemic approaches to health

  Chairholder: Mélanie Lemire (Dept. of Social and Preventive Medicine)

- Sentinel North partnership research chair on sleep pharmacometabolism

  Chairholder: Natalie Jane Michael (Fac. of Pharmacy)

- Sentinel North research chair in the neurobiology of stress and resilience

  Chairholder: Caroline Ménard (Dept. of Psychiatry and Neurosciences)

- Sentinel North research chair on the applications and theory of network analysis

  Chairholder: Antoine Allard (Dept. of Physics, Physical Engineering, and Optics)

- Sentinel North research chair on the relations with Inuit societies

  Chairholder: Caroline Hervé (Dept. of Anthropology)

- Joint International Research Unit in child neural development and psychiatry

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Acknowledgments
The following research team members contributed to the review of the scientific highlights presented in this chapter:

Antoine Allard, Myrtille Bayle, Myriam Blais, Claude Demers, Caroline Duchaine, Paul De Koninck, Benoît Gosselin, Maripier Isabelle, Benoît Labonté, Mélanie Lemire, Caroline Ménard, Mathieu Morissette, Gina Muckle, François Paquet-Mercier, Martin Roy and Geneviève Vachon.

We also thank Caroline Ménard and Gina Muckle for their comments on the introduction and Natalia Poliakova for her revision on the chapter.

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