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Permafrost Challenges and Solutions: A Network-Driven Approach in Canada

2019-2025

NSERC PermafrostNet

DRAFT MOCK-UP FOR DISCUSSION

Foreword

The following compendium provides a comprehensive overview of permafrost research projects conducted by NSERC PermafrostNet between 2019 and 2025. A collection of 40 project summaries have been compiled and organized under the five network themes of NSERC PermafrostNet. NSERC PermafrostNet was a strategic partnership network funded for 5 years from 2019 to 2024. This compendium covers the outcomes of the network projects as well as the overall outcome of a network approach to permafrost research. The reports and accompanying publications each have an associated persistent identifier, such as a DOI.

To cite this report:

[INSERT CITATION HERE]

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Part 1: Network and partnership

Message from the Scientific Director

Permafrost underlies 35–50% of the Canadian land surface and is a defining characteristic of Canada's North. Most of the permafrost region will experience persistent loss of ground ice through the 21st century, leading to irreversible landscape transformations, profound challenges for infrastructure, and threats to the health and livelihoods of northerners.

NSERC PermafrostNet was created to help Canada prepare for permafrost change by transforming permafrost science, aligning it with decision-making, and developing solutions for adaptation. We achieve this through training the next generation of permafrost experts, building connections between researchers and stakeholders, and rapidly translating knowledge into action.

Over 40 students and postdoctoral fellows have been working across five research themes to quantify, understand and predict permafrost thaw and its consequences. As a result, the network has made significant advances in areas like data interoperability, numerical modelling, remote sensing, and designing practical solutions to adapt infrastructure and communities.

The network developed partnerships with over 40 organizations, including all levels of government, industry, Indigenous groups, and international collaborators. These connections ensure this research addresses real-world needs and that new knowledge can be rapidly implemented.

As we conclude the mandate of the network, I am confident NSERC PermafrostNet has delivered innovative science and the highly qualified personnel that Canada requires to tackle the impacts of thawing permafrost. We aim to leave a legacy where permafrost science has the resources, coordination, and partners needed to support adaptation and sustainable development across the North.

Dr. Stephan Gruber, Scientific Director

Message from the Chair of the Board

Permafrost thaw is one of the most consequential impacts of climate change across the Canadian North. Its effects on landscapes, infrastructure, food security, ecosystems and more present interconnected scientific, engineering, social and economic challenges.

A network approach is key to tackling issues of this complexity. By bringing together expertise from multiple disciplines and institutions to collaborate with stakeholders, NSERC PermafrostNet has been developing solutions not possible in isolation.

Over 40 students, northern research assistants and postdocs have gained hands-on training in this vibrant research community. Partners from government, industry and Indigenous organizations have ensured the network stays aligned with user needs and that new knowledge can inform decision-making.

Despite the upheaval of the COVID-19 pandemic, NSERC PermafrostNet adapted and laid vital foundations for the future of co-ordinated permafrost research in Canada. Advanced data systems now connect observations from across the permafrost zone. Novel remote sensing methods are tracking landscape hazards. And new modeling tools are projecting future conditions.

Canada can now look forward to the future confident permafrost research can deliver innovative science and highly qualified personnel needed to tackle permafrost challenges across the North.

Dr. Janet King, Chair of the Board

The network

NSERC PermafrostNet was a six-year strategic partnership network supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) that started in June 2019.

The network involved:

- 12 Canadian universities
- Over 40 partner organizations
- Over 40 students, Northern research assistants and postdoctoral fellows

The network took a collaborative approach to permafrost research and training, bringing together expertise from multiple disciplines to work closely with stakeholders. This integration of research, training and partnerships has delivered knowledge, data, and tools to support adaptation to permafrost thaw across Northern Canada.

It was led by Scientific Director Dr. Stephan Gruber (Carleton University) and governed by a Board of Directors chaired by Dr. Janet King. The network was hosted by Carleton University and was overseen, advised and managed by a number of governing bodies and individuals, including a Board of Directors, a Scientific committee, Knowledge Mobilization and Communication committee, and Equity, Diversity and Inclusion committee. The network was also further supported by a Deputy Scientific Director, Theme leaders, a Director of Operations, a Data Scientist and a number of subcommittees and additional governing bodies, such as the Strategy Committee and the graduate student and post-doctoral advisory committee.

The network research focused on the big questions: Where and when is permafrost thaw occurring in Canada and what are the hazards arising from such change? To achieve this the research was organized into five interwoven themes requiring a critical mass and diversity of expertise that no single research group or government agency has. The network was a multidisciplinary arrangement of complementary expertise that works together with three aims; to quantify, understand and predict permafrost thaw and its consequences; to connect spatial scales from individual sites up to Earth-system modeling; and to prototype reliable and useful data and knowledge products for scientific research, engineering and application in government, communities, and industry. The research conducted by the network has been laying the foundation for advances in permafrost science and engineering practice across diverse topics such as data interoperability, numerical modelling and prediction, and practical applications of scientific theories for adaptation to permafrost thaw.

Over 40 partner organizations have supported this networked permafrost research with direct contributions of $X,XXX,XXX, and in-kind contributions to research activities totalling $X,XXX,XXX.

Key funders:

- Natural Sciences and Engineering Research Council of Canada (NSERC)
- Partner universities
- Government agencies
- Industry

Partners included:

- Federal, provincial, and territorial agencies
- Standards organizations
- Industry
- Indigenous governments and organizations
- Research networks
- International collaborators

Permafrost in Canada

Introduction

Permafrost—ground that remains frozen for at least two consecutive years—underlies about half of Canada. In the North, it shapes landscapes, ecosystems, infrastructure design and more.

Air temperatures in the permafrost region have increased at more than twice the global rate over the past 50 years. Widespread permafrost thaw is projected across the Canadian North this century.

Impacts of thawing permafrost include:

- Landscape changes from subsidence and erosion
- Damage to buildings, roads and pipelines
- Release of carbon dioxide and methane
- Mobilization of mercury
- Changes in wildlife habitat and hydrology

These effects interact, sometimes producing cascading impacts. For example, thawing can destabilize the ground, triggering erosion that affects rivers and infrastructure.

Understanding complex linkages between climatic, ecological, and human systems is key to adaptation. NSERC PermafrostNet research aims to provide the knowledge base to minimize risks and build resilience.

The network takes an integrated approach across five research themes:

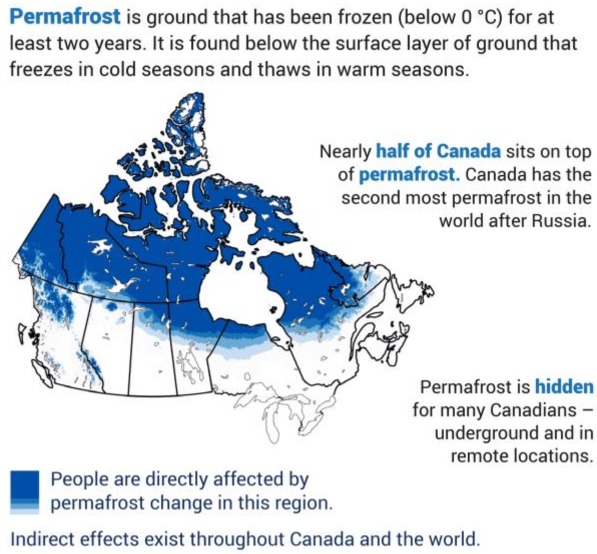
- Theme 1: Characterization of permafrost
- Theme 2: Monitoring permafrost change
- Theme 3: Prediction of permafrost characteristics and change
- Theme 4: Hazards and impacts of permafrost thaw
- Theme 5: Adaptation to permafrost thaw

NSERC PermafrostNet's research themes collaboratively work to achieve three overarching objectives: i) quantify, understand, and predict permafrost thaw and its consequences; ii) connect spatial scales from individual sites to national-scale prediction and assessment and from field measurements to satellite-based remote sensing and Earth-system modeling; and iii) prototype reliable and useful data and knowledge products for stakeholders and develop relevant next practices with them. Research mobilization and training of students/postdocs is woven throughout these themes to maximize impact. Partnership is key to ensure outputs are useful and used.

The network intends to leave a legacy where permafrost research has the resources, coordination, and connections to support evidence-based decisions into the future.

Permafrost Underlies Vast Regions of Canada's North

Permafrost – ground that remains frozen for at least two consecutive years – is a defining feature of Canada's northern landscapes. Discontinuous, sporadic, and isolated patches of permafrost underlie around 50% of Canada, while continuous permafrost blankets much of the Yukon, Northwest Territories, Nunavut, and northern Quebec and Labrador. The southern boundary of permafrost roughly follows the southern edges of the discontinuous and sporadic zones, but its precise location varies considerably based on local factors like snow cover, vegetation, and soil properties.



Permafrost Regions Display Distinct Characteristics

Continuous permafrost areas have permafrost underneath 90-100% of the land surface. They typically occur where mean annual air temperatures are below -8°C. The ground remains frozen year-round, although an active layer up to 4 metres deep thaws seasonally. In discontinuous zones, permafrost underlies 50-90% of the land and is generally found where mean annual temperatures are -8°C to 0°C. Discontinuous permafrost occurs as isolated patches of frozen ground amid unfrozen areas. Sporadic permafrost covers 10-50% of the landscape and is typically found where mean annual air temperatures range from 0°C to 2°C. Isolated permafrost describes scattered frozen patches covering less than 10% of the surface in areas where mean annual temperatures exceed -2°C.

Ground Ice Content Varies Across Regions

A defining characteristic of permafrost is ground ice, which cement together soil particles. Massive ice bodies can also occur, including wedge ice and pingos. The amount and type of ground ice depends on the climate and environment when it formed. Ice-rich permafrost contains visible ice, while ice-poor permafrost has ice mainly between sediment grains. Ice-rich permafrost is common in northern Yukon and the western Arctic due to harsher climate. Abundant wedge ice builds up in flat, fine-grained sediments. Coastal lowlands and river valleys also tend to have considerable excess ice. Ice-poor permafrost with lower excess ice content is more widespread in eastern and high Arctic regions.

Permafrost Keeps Carbon Locked in Northern Soils

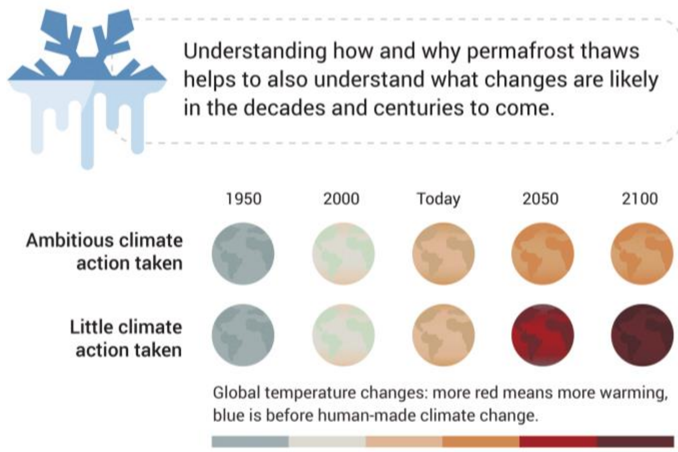
Permanently frozen ground restricts decomposition, causing northern soils to store large amounts of organic carbon. Estimates suggest northern permafrost regions contain 1700 billion tonnes of organic carbon, making it one of the largest carbon pools on Earth. Plant remains accumulate because restricted drainage in permafrost creates waterlogged conditions where decomposition is slow. As well, cold temperatures limit microbial breakdown of organic matter in permafrost. Much of this carbon has been locked away for thousands of years by persistent ground freezing.

Permafrost Shapes Northern Landscapes and Ecosystems

The presence of permafrost strongly influences northern hydrology, landscapes, vegetation, and habitat. Its freezing cement holds together varied materials like loose sediment or rock on slopes. Extensive lowland areas underlain by ice-rich permafrost impede drainage, creating millions of lakes and wetlands surrounded by drier raised areas with better drainage. Slow decomposition in waterlogged, frozen ground builds up thick organic soils. Subsidence of the ground surface occurs when the supporting matrix of ground ice thaws. The unique conditions imposed by permafrost lead to specialized cold-adapted ecosystems like peatlands and patterned ground with sorted stone circles and other ground patterns.

Thawing Permafrost Transforms Landscapes

Rising air temperatures are causing widespread warming and thaw of permafrost. Over the past 50 years, temperatures in northern Canada have increased around 3°C – more than three times the global average. Thawing permafrost unlocks landscapes frozen for millennia, mobilizing carbon and nutrients. Abrupt thaw features like sinkholes can form when ground ice melts, while slow subsidence of the land surface accelerates erosion and drainage. Loss of permafrost alters water flows, wildfire regimes and ecological dynamics with cascading impacts. Coastal erosion threatens communities as rising sea levels interact with degrading icy shores.



Global air temperatures will continue to rise for decades. Without ambitious climate action, they will keep rising. Thawing permafrost will cause serious problems to land structure, infrastructure, wildlife, and Northern communities.

Billions of tonnes of organic carbon in thawing permafrost are vulnerable to decomposition and release as carbon dioxide and methane, amplifying global climate change. However, severe wildfires on thawed ground can offset this by producing refractory carbon. Understanding complex interactions between climate, hydrology, ecosystems, and human activity is key to predicting impacts.

Permafrost Threatens Infrastructure Across the North

Thawing permafrost presents substantial engineering challenges and damage risks. Infrastructure like buildings, roads, pipelines, and airports are often designed assuming permafrost will remain frozen. Thaw settlement beneath foundations can destabilize structures. Erosion of coastal and river bluffs threatens facilities and disrupts supply chains. Construction and transportation in discontinuous zones must navigate patchy frozen ground with variable bearing capacity.

Rapid warming means infrastructure originally engineered for frozen conditions is now threatened across Canada's North. Affected facilities include transportation networks like highways and runways, municipal buildings, industrial facilities, mines, waste storage, and community services like water, sewer, and energy. Undermining of infrastructure can in turn accelerate permafrost thaw through heat transfer.

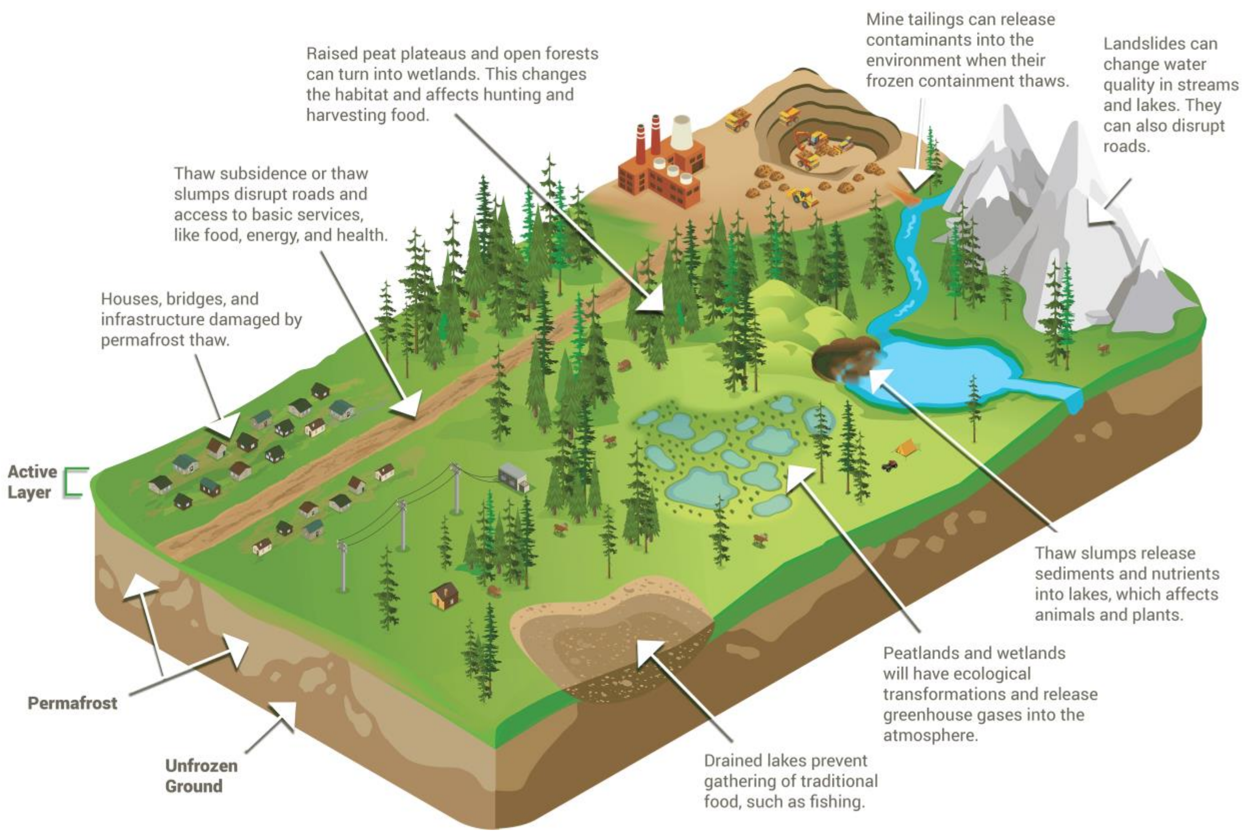
Adapting to Permafrost Change Requires Integrated Knowledge

Understanding complex interactions between climatic, ecological, and human systems is key to adaptation. Integrated knowledge allows weaving together diverse issues like landscape hazards, infrastructure resilience, groundwater flows, carbon feedbacks, policy responses, and Indigenous knowledge.

Projections of future change and associated impacts require ground truthing today's conditions using field studies, new geospatial datasets, and advanced monitoring. Engagement with communities ensures local priorities and needs are reflected. Novel engineering solutions can stabilize infrastructure, informed by improved predictive modelling.

Coordinated networks like NSERC PermafrostNet foster the cross-disciplinary collaboration and stakeholder alliances needed to deliver adaptation pathways. Their legacy will be a new generation of expertise and relationships to support evidence-based decisions in addressing unprecedented change.

Northerners are already experiencing the rapidly increasing impacts of permafrost thaw. Here are some examples of the changes that can happen when permafrost thaws.



Considerations for building and applying permafrost knowledge in Canada

Building robust knowledge of Canada's extensive and diverse permafrost regions requires coordinated networks to connect researchers, communities, governments, and industry. Key considerations include:

Engaging Partners in Setting Priorities

Inclusive collaboration ensures research addresses user needs. Partners like Indigenous governments and northern municipalities can identify high-priority questions and co-develop solutions. Their insights guide monitoring and modelling to focus on vulnerable locations and infrastructure. Ongoing dialogue and reciprocal learning is key.

Integrating Scientific Disciplines and Knowledge Systems

Interactions between climate, ecology, hydrology, infrastructure and more require linking physical and social sciences with Indigenous knowledge. Holistic understanding emerges from combining community observations, geospatial data, monitoring, modelling, and field studies. Intentionally building connections across disciplines and knowledge systems enables a systems perspective.

Coordinating Logistics and Expertise

Undertaking field research across the remote North demands substantial logistical support. Coordinating resources and expertise across regions provides efficiencies. Centralized field camps allow sharing of equipment and expertise. Uniform data collection protocols facilitate integration. Core facilities provide consistent sample analysis otherwise limited to southern labs.

Developing Responsive Monitoring Networks

Sparse monitoring networks limit understanding permafrost change. Prioritizing key variables and locations for integrated monitoring is essential. Expanding community-based efforts complements intensive research sites. Remote sensing and geophysical imaging provide wide coverage. Systematically processing and delivering this data informs adaptation.

Enhancing Data Interoperability

Varied data formats and systems inhibit combining disparate datasets needed to characterize permafrost at multiple scales. Common standards and interconnected databases enable integrated analysis. FAIR principles of open data improve discovery and reuse. Data management expertise and tools tailored to community needs simplify contributions.

Bridging Research and Decision-Making

Usable knowledge products and open communication channels help bridge research and action. Climate services delivering localized projections and uncertainty quantification directly inform planning. Decision-makers involved in research steer outputs to user needs. Rapid dissemination channels like online platforms and media engage diverse audiences.

Training Future Generations

Hands-on field experience, interdisciplinary coursework and mentorship equip graduates to lead future efforts. Exposure to community needs builds mutually beneficial relationships. Holistic training integrates technical skills with communication, collaboration, and project management. International exchanges provide perspective.

Supporting Early Career Researchers

Postdoctoral fellowships enable continued development of specialized expertise. Professional development opportunities build leadership capacity. Resources for pilot studies and equipment access support emerging research directions. For junior faculty, lower teaching loads and graduate student support facilitate establishment of northern research programs.

Sustaining Partnerships and Infrastructure

Partnerships between universities, governments, communities, and industry need ongoing nurturing through regular interactions and co-learning. Field stations, research platforms, databases and community-based monitoring require secure multi-year funding. Networks develop relationships, data and technical capacity that require maintenance beyond short project cycles.

Planning for Effective Knowledge Transfer

Timely dissemination ensures findings reach end users and avoids research bottlenecks. Multi-directional knowledge sharing recognizes community priorities. Evaluation guides ongoing improvement. Legacy planning, including training networks and data curation, delivers lasting benefits. Intentional design brings together players across the knowledge-to-action spectrum.

A legacy of partnerships, coordination and investments across these areas can provide the strong foundation needed to address the research, engineering, and adaptation needs arising from unprecedented change in Canada’s permafrost regions.

Building a permafrost knowledge partnership

It is clear that a single research group, government agency or industry cannot tackle the challenges presented by widespread and persistent thaw of permafrost alone. The establishment of a pan-Canadian network in 2019 has helped consolidate science, local knowledge and learning, and professional practice so that it provides relevant information at regional and national scales to wider audiences.

A number of workshops and projects led up to a seminal workshop in February 2017. This event looked at how the range of stakeholders concerned can work together to address the big challenges and opportunities in the permafrost community. The workshop was based on a preparation survey, cross-checked with previous permafrost workshops in Canada, that highlighted eight focus areas for discussion and action.

A diverse community of almost 60 individuals met at Carleton University, representing Federal, Yukon, Northwest Territories and Nunavut Governments, researchers from Canadian universities, and the private sector. The workshop objectives were to gain a shared understanding of what a Canadian permafrost network would work towards and to provide opportunities for people to network and build relationships. We wanted to find out what was needed to add value – rather than adding control. Through moderated discussions, the workshop provided concrete outcomes on the development of a permafrost network for Canada.

The network came up with an initial purpose, "*To advance knowledge about changing permafrost environments*". To address the broad membership and geographic distance, it was proposed that there should be a Secretariat in the Ottawa Region, likely at Carleton University, in addition to strong presence in the territories. At a minimum, the workshop participants felt that the network needed diverse membership, a director and/or paid coordinator, a website, a clear vision to help grow the network and to link with other organizations. Beyond these baseline activities, attendees envisioned the network having a multifaceted presence, including lobbying, providing education and outreach and data storage/sharing services.

Part 2: Permafrost Data

Data for permafrost

Data is an important element in permafrost research. The network has prototyped reliable and useful data and knowledge products for stakeholders and integrate field data with simulation. This has been achieved through the shared use of network resources including a platform for permafrost data science and simulation.

Data Interoperability

Using standards for your permafrost data when sharing or publishing it is one of the ways to make your data more discoverable and reusable by others.

Participants at the 2020 Permafrost Data Workshop identified access to standardized data and the discoverability of existing data as two of their main data-related challenges. NSERC PermafrostNet's subsequently created recommendations for sharing and publishing permafrost data.

Here we focus on ground temperature data and geotechnical measurements. These recommendations will promote data interoperability within the network and the broader community.

Part 3: Networked Research

Theme 1: Characterization of permafrost

Objective: Improve understanding of ground ice and properties to better represent thaw processes and provide inputs to predictive modelling.

Approach: Development of national ground ice and permafrost databases; novel geophysical techniques; analysis of permafrost cores.

Outcomes:

- Permafrost Information Network of Ground Observations (PINGO) collates borehole and related data to characterize permafrost and ground ice distribution. This enables better spatial analysis and model inputs.

- New databases compile information from electrical resistivity and permafrost core analysis. These datasets aid interpretation and tracking of permafrost change over time.

- Advanced core scanning provides improved quantification of ground ice content and properties.

- Studies of vulnerable landforms like peat plateaus and thaw slumps add to knowledge of how terrain responds to thawing.

Next challenges: Expand databases across Canada's diverse regions and permafrost types; integrate new characterization data to improve prediction of terrain sensitivity.

Theme 1 (Characterization) is devoted to improving the understanding of ground ice loss and its consequences through characterization of permafrost in Canada so that prediction can represent processes during thaw and have relevant subsurface input such as ground ice content. Theme 1 has been creating the Permafrost Information Network of Ground Observations (PINGO), a set of interoperable databases that can be jointly interrogated, along with the network data scientist (NDS; N. Brown). PINGO is one of the main network data products; the development of which relies upon Theme 1 for creation of the PINGO data standards and best practices documentation, with contributions from Theme 2. PINGO will be, or is already, used by the other themes as well as made available to researchers and stakeholders more broadly. It currently comprises an ERDDAP server for interoperable data exchange, a relational database (directly accessible only by those within the network), and an online data browser that can access each of these resources. As a way to promote the adoption of this technology stack by other permafrost researchers, the NDS has developed a containerized Docker environment which makes it easy to deploy the relational database and ancillary data input interface. Theme 1 has also been developing a database of electrical resistivity tomography (ERT) surveys whose results can be used to characterize permafrost conditions and track change. The Canadian Permafrost Electrical Resistivity Survey (CPERS) next practices and database will maximize interoperability with PINGO. Its development is aided by the NDS around technical requirements of CPERS and recommendations to achieve interoperability with other data centres and an International Permafrost Association (IPA) database currently under development. Other Theme 1 projects have been generating new datasets to contribute to PINGO that characterize thaw settlement and thaw consolidation and update the Ground Ice Potential Map (GRIP) for the Mackenzie Valley and glacial lakes Mackenzie and McConnell, the colluvial hillslope yedoma of the unglaciated Klondike, and the eastern Canadian Arctic polar deserts. As the outputs from Theme 1, such as PINGO, CPERS and the data underpinning GRIP mature, these databases will be essential for other Themes' activities. Theme 1 has also been leading an effort of the Canadian Permafrost Association (CPA) to create a revised version of the Glossary of Permafrost and Related Ground Ice Terms, including contributions from Co-Investigators in Themes 3 and 4, the NDS and network partners (Lewkowicz 2021). In addition to updating the glossary definitions, the revised glossary will contribute to data interoperability efforts. Through experience gained collaborating with CCADI, the NDS is helping to structure the glossary in a way that is compatible with the simple knowledge organization system (SKOS) standard. This means that in addition to a static document, the glossary will exist as a machine-readable web resource and controlled vocabulary, which will make it easier to create consistent metadata, search for permafrost data, and link knowledge to other disciplines. This technology is already used by a number of other organizations, including the British Oceanographic Data Centre, CCADI and the Australian Research Data Commons.

Work in Theme 1 has produced results of significance, including a new rapid, non-destructive method of permafrost core characterization using multi-sensor core logging and industrial computed tomography (CT) scanning for permafrost (Froese 2021). As part of CPERS, Theme 1 researchers have been establishing best practices for data acquisition and processing ERT surveys, which are essential to making justifiable interpretations of permafrost conditions and how they are changing.

ERT is used to map the resistivity of the subsurface which can help identify frozen regions. ERT survey design (electrode spacing, number of electrodes used, and array type) plays a big role in how well key features are resolved. HQP T. Herring and Prof. A. Lewkowicz (Herring 2021a) examined the use of forward modelling, which combines a resistivity model, physics, and survey design to generate a simulation of ERT data. The forward modelling tool was demonstrated to be valuable to help guide survey design and aid interpretation of results.

Theme 1 HQP T. Herring led one of the working parties in an International Permafrost Association (IPA) action group creating an international database of ERT surveys to help researchers map spatial trends in permafrost conditions and see how permafrost is changing over time in response to climate warming. A global database of resistivity surveys can map permafrost conditions over large spatial and temporal scales, but all datasets must be processed in a consistent way. Their project is creating a workflow to process ERT surveys of permafrost in a consistent way that will work for most cases without modification. There are two key steps in ERT data processing: filtering and inversion. A new processing pipeline has been created that makes judicious choices in both steps to produce a generalized algorithm that works well for ERT data collected in a diverse range of permafrost environments (Herring 2021b).

Theme 2: Monitoring of permafrost change

Objective: Detect and quantify changes occurring across the landscape by combining field measurements with remote sensing.

Approach: Borehole monitoring; novel remote sensing with satellite, drone, and airborne data; incorporation of Indigenous knowledge.

Outcomes:

- New methods developed to process and interpret remote sensing data over permafrost areas.

- Borehole databases integrated into online platforms for data analysis and model validation.

- Case studies reveal local impacts, like extensive ponding, and landscape-scale changes detectable from space.

- Outreach establishes community priorities to guide research.

Next challenges: Expanding monitoring networks to fill spatial gaps; regular acquisition and processing of remote sensing data; responding to community needs.

Theme 2 (Monitoring) has the objective of revealing and quantifying permafrost change in Canada and understanding its varying rates and expressions at the land surface. Close linkages between Theme 1 and 2 are emerging and Theme 2 has already integrated borehole data from an early version of PINGO into the Permafrost Data Science Platform (PDSP). The common approach afforded by PDSP provides uniform and reliable access to databases and tools for data processing, visualization, and simulation. The PhD project of Highly Qualified Person (HQP) F. Ghiami-Shomami (T2-PhD5; these project codes were used in the network proposal and can also be found here in Table 1) incorporates analysis of temperature-depth profiles with additional observations such as surface subsidence to develop, test and automate new methods and synthesize spatio-temporal patterns of change to generate a national picture of permafrost thaw through site-specific observations. Other Theme 2 projects are broadly integrating expertise across themes. The SFU radar-optical system forms the basis of two projects in Theme 2; however network members across Themes 1, 2, and 4 have been contributing to plan, develop and refine the utility of the technique to investigate permafrost change along linear infrastructure, including selection of field sites for method evaluation.

Theme 2 HQP U. Ahmed's work has led to refinements in synthetic aperture radar (SAR) trajectories using optical Foto detection and ranging (Fodar™) data (Usman, Rabus and Kubanski 2021). Fodar, when fully calibrated, can produce digital elevation models (DEMs) with an accuracy superior to available global DEMs and comparable to DEMs derived from conventional photogrammetry and even lidar, but at much lower operational costs. The derived DEMs can be used to monitor landscape change due to permafrost degradation.

Theme 3: Prediction of permafrost change

Objective: Improve accuracy of models projecting future conditions and develop climate services to deliver predictions.

Approach: New model development and evaluation methods; large ensemble simulations; focus on translating outputs for decisions.

Outcomes:

- More comprehensive representation of key processes, like excess ground ice thaw and vegetation shifts.

- New testing approaches quantify model uncertainty and guide improvement.

- Climate services prototype provides information on future ground thermal regime tailored for infrastructure design.

- Software tools created to run large model ensembles on supercomputers and process results.

Next challenges: Incorporate expanded monitoring data into models; ensemble simulations across broader regions; co-development of climate services with users.

Theme 3 (Prediction) improves the accuracy and delivery of transient permafrost simulation so that its results can support stakeholder needs at local and national scales. Much of the work in Theme 3 has thus far been devoted to developing the needed modelling systems, including integration of observation-based information from Themes 1 and 2 to produce data products for Themes 4 and 5. Theme 3 has completed one MSc project devoted to understanding the changing ice regime of thermokarst lakes in the Old Crow Flats, Yukon (Shaposhnikova 2021). Other Theme 3 projects build upon Theme 1 data products such as PINGO for model development, validation, and testing. Theme 3 involves developing permafrost ensemble simulations and a framework to provide more meaningful ways to measure permafrost model performance and enable the simulations to be accompanied by a measure of confidence. Additionally, Theme 3 projects are contributing to development of the Canadian Land Surface Scheme, including Biogeochemical Cycles (CLASSIC), an open-source community land surface model integrated into the framework. Another Theme 3 project is developing a methodology in conjunction with Theme 1 that will integrate their borehole ground ice observations to produce a new version of GRIP based on machine learning. In related work, A. Castagner (affiliated HQP) has developed a method for statistical estimation of excess ice content from geotechnical data, important information for initial conditions used in ensemble simulations of permafrost thaw.

Theme 3 MSc HQP M. Shaposhnikova completed a novel study to introduce and implement a temporal deep learning approach for the analysis of time series of synthetic aperture radar (SAR) imagery (Shaposhnikova 2021). She used a combination of Sentinel 1, ERS 1/2, and RADARSAT 1 SAR imagery for the Old Crow Flats, Yukon, Canada to create an extensive annotated dataset of SAR time-series labeled as either bedfast ice, floating ice or land (example output shown in Figure 2). This dataset was then used to train a temporal convolutional neural network (TempCNN). Lake ice is a fundamental part of the freshwater processes in cold regions and a sensitive indicator of climate change. As such, in light of the recent climate warming, monitoring of lake ice in Arctic and sub-Arctic regions is becoming increasingly important. Many shallow Arctic lakes and ponds of thermokarst origin freeze to bed in the winter months, maintaining the underlying permafrost in its frozen state. However, as air temperatures rise and precipitation increases, fewer lakes are expected to develop bedfast ice. The TempCNN results found extensive transition to bedfast ice caused by a growing number of catastrophic drainages within the examined time period (1993 to 2021) brought on by climate warming and thermokarst processes.

Other advancements in modelling of permafrost change centred on improving model representation of land cover change and its influence on permafrost. The Canadian Land Surface Scheme including Biogeochemical Cycles (CLASSIC) is a major component of Theme 3 activities but is missing some important vegetation types common in permafrost environments. (Meyer et al. 2021) introduced new shrub and sedge plant functional types (PFTs; a form of metaspecies) into CLASSIC and evaluated the parameterizations at Daring Lake, a highly instrumented site in the Northwest Territories. The inclusion of these PFTs improved the model simulated ground temperatures, surface energy and water fluxes against observations.

The prediction of permafrost characteristics and future permafrost change is important because it underpins evidence-based decision-making for adaptation. It is the basis for minimizing risk by reducing exposure in preferring some locations over others, reducing vulnerability in designing infrastructure and realistically planning maintenance costs. Among the important advancements needed to make simulation results more useful for adaptation, a better representation of key phenomena and processes in models is important for accurately translating climate change into anticipated impacts. To address this, Theme 3 has been advancing the process representation of CLASSIC, which also forms the land surface component of the Canadian Earth System Model (CanESM). The advancements in CLASSIC then directly impact the quality of future projections by CanESM and its family of models, including the Canadian Regional Climate Model. The specific advancements to CLASSIC already completed include incorporating shrubs (Meyer et al. 2021) to improve simulations of the impact of vegetation on the state of the Canadian permafrost region.

Theme 4: Hazards and impacts associated with permafrost thaw

Objective: Advance understanding of hazards arising from thaw to improve risk assessment and adaptation.

Approach: Field studies, remote sensing monitoring, modelling of vulnerable terrain; focus on implications for infrastructure and water quality.

Outcomes:

- New insights into erosion of riverbanks, coastlines, and other landscapes vulnerable to thawing.

- Better quantification of impacts on infrastructure like roads and rail embankments.

- Advances in remote sensing to monitor hazard evolution and model future risk areas.

- Initial assessments of thaw effects on mercury mobilization and hydrochemistry.

Next challenges: Incorporating findings into hazard maps/models; predicting interactions and cascading effects; monitoring change over larger regions.

Theme 4 (Hazards and Impacts) seeks to understand the relevance and controls of the impacts and hazards driven by permafrost thaw and improve their prediction to support adaptation. The PhD project of HQP E. Stewart-Jones (T4-PhD1), devoted to improving understanding and prediction of thaw-induced mass movement in steep mountains, contributes to Theme 1's PINGO, as well as using simulation tools from Theme 3. Another Theme 4 PhD project is developing data products which are being integrated into PINGO with the assistance of the NDS, as well as next practices with respect to permafrost thermal characteristics and change in the mountains of Western Canada. Along with the NDS, the project is also producing open-source software tools for data handling: *HorizonPy* is a program for digitizing horizon lines from fisheye photography so that they can be used in surface energy-balance modelling and *tempcf* is a toolkit for cleaning and standardizing permafrost thermal data. Theme 4 is closely linked with Theme 5 through regular cross-theme meetings and project collaborations such as between the PhD project devoted to "Understanding and prediction of thaw-driven flash flooding and water quality change" (T4-PhD5) and a new Theme 5 project titled "Land use planning and mass-wasting hazards near Fort Severn and water quality change" (T5-PhD4).

Theme 4 HQP A. Clark studied a stretch of coastline off Richard's Island, Northwest Territories, that contains multiple retrogressive thaw slumps (RTSs) with varying degrees of activity (Clark et al. 2021). Ground movement information was generated by multi-temporal 2D and 3D geomorphic analysis of data from Remotely Piloted Aircraft Systems-Structure-from-Motion (RPAS-SfM) flights. Clark's study furthers geomorphological understanding of RTS processes by highlighting the complex relationship between planimetric and volumetric change along rapidly retreating Arctic coasts and demonstrates advancements in measurement practices for RPAS-SfM data sets. The development of these new remote techniques for early detection and monitoring of hazards can enable a reduction in their impact.

Theme 5: Adaptation to permafrost thaw

Objective: Develop knowledge to support adaptation of infrastructure and communities affected by changing permafrost.

Approach: Site investigations of infrastructure performance; projections of maintenance costs; engagement with communities.

Outcomes:

- Evaluation of techniques like thermosyphons and snow compaction to stabilize infrastructure foundations.

- Regional analysis highlights increased maintenance costs associated with permafrost thaw.

- Implementation of solutions like geocells to reinforce rail embankments prone to thaw settlement.

- Community partnerships guide research priorities regarding landscape change and water quality.

Next challenges: Expanding analysis of adaptation options across infrastructure types and climates; cost-benefit analysis of solutions; responding to community adaptation needs.

Theme 5 (Adaptation) seeks to support northerners in adaptation to permafrost in transition. Theme 5's close linkage to Theme 4 resulted in a HQP cross-posted between themes (A. Kirkwood – T5-PhD4).

Numerous techniques have been developed to control ground temperatures and preserve permafrost underlying infrastructure. Generally, these techniques attempt to either limit heat intake or extract heat from the ground column. Some examples of the former include installing insulation to increase the thermal resistance of the infrastructure surface, covering it with high albedo surface materials, or installing sun sheds to reduce absorbed solar radiation. The Theme 5 MSc project of P. Jardine examines snowpack compaction as a method of improving the stability of infrastructure built in permafrost terrain. Snow typically has a lower thermal conductivity than ground surface materials. This causes most snowpacks to act as surface insulation, limiting heat flow out of the ground during the freezing season. The extent of insulation provided by the snowpack is negatively associated with the density of the snowpack and positively associated with its depth. HQP Jardine's MSc research assists highway maintenance staff in evaluating if snow compaction is an effective tool for mitigation of permafrost thaw beside highway embankments, including how repeated snowpack compaction affects snowpack structure and density and how modifying the timing and frequency of snowpack compaction impacts its effects on ground temperatures, snowpack structure and snowpack density.

An affiliated Theme researcher S. Gagnon, (a postdoctoral fellow supervised by D. Fortier) worked on a mitigation technique to control permafrost degradation under road embankments.

The Theme 5 MSc project of A. Schetselaar has found that climate change accounts for up to 75% of the cost of all highway maintenance for the Yukon Government (Schetselaar 2022).

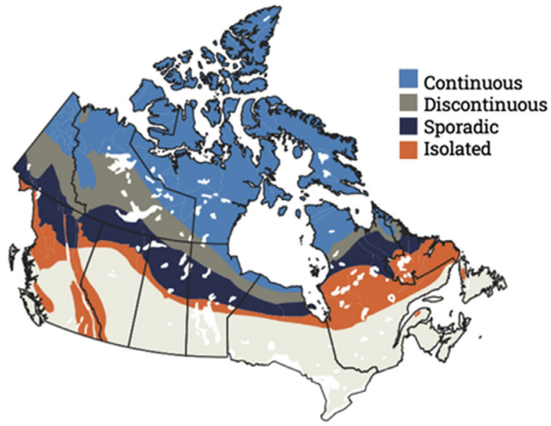
Substantial spatial variability in the natural environment means that these climate-related maintenance costs vary from site to site. Slides and washouts are particularly costly climate-sensitive catastrophic events. HQP Schetselaar led another study that examined historical climate model outputs and future climate projections from 29 scenarios run by seven ESMs for the Yukon and Mackenzie Valley and compared them with the observed record (Schetselaar 2021). Based upon four sites in the Yukon and N.W.T., projections of temperature may be following the higher future warming scenarios. This leads to the recommendation for increased investment in adaptation strategies such as design of thermosyphons to cope with rising winter temperatures and site investigation to identify thaw-stable sites. These early results are of significance for Canada, for example, by informing decisions related to Goal 3 - "Adapt to the impacts of climate change" - of Our Clean Future, the Yukon strategy for climate change, energy and a green economy.

The Hudson Bay Lowlands (HBL) may be one of the largest mercury (Hg) pools in the permafrost zone according to recent estimates. This is of concern to residents of the HBL who consume local fish due to the potential for this inorganic Hg to be converted to its organic, bioavailable, bioaccumulative and neurotoxic form methylmercury (MeHg) as permafrost in the HBL thaws. However, little is known about the abundance and distribution of MeHg, and it is unclear how permafrost degradation relates to the release and potential methylation of Hg. A part of their PhD project, HQP A. Kirkwood has been working to enhance scientific knowledge related to mercury mobilization potential and to linkages between permafrost thaw and mudflow developments in the Hudson Bay Lowlands. In both cases, they are developing spatial datasets that improve ability to understand and predict where related hazards may take place. This PhD project uses 35 peat cores (800 subsamples) collected in the continuous permafrost zone of northern Manitoba and Ontario at sites representing intact and degrading permafrost features (e.g., palsas/plateaus and fens) to map total mercury distribution in the HBL and relate environmental conditions created by thaw to the production of methylmercury. This work can be used in combination with the mapping of thaw-sensitive terrain to identify areas where mercury methylation may impact adjacent aquatic ecosystems if disturbed. Early results suggest Hg concentrations in the top 100 centimetres of the peat profile are lower than previous estimates of Hg derived from SOC pools for the circumpolar north with a storage of approximately nine milligram tal Hg metres squared (Kirkwood 2021).

Part 4: Project Summaries

An introduction to the project summaries. The following projects were conducted by trainees ranging from master’s students to post-doctoral fellows. In some cases, they conducted field work in the North of Canada and for other projects they relied completely on data accessible remotely by computer.

Establishing a Canadian database of geoelectrical surveys of permafrost.



Teddi Herring, Antoni G. Lewkowicz, University of Ottawa

Keywords: Geophysics, electrical resistivity tomography, database, monitoring, climate change.

Study locations: Canada-wide

The main outcome of this project is a database of electrical resistivity tomography (ERT) surveys of permafrost in Canada. These geophysical surveys are often used to characterize permafrost extent and conditions, but until now there has been no framework for data sharing. We created the Canadian Permafrost Electrical Resistivity (CPERS) database to archive surveys in a standardized way. The database enables researchers, practitioners, and community members to easily share and access data, improving our collective understanding of permafrost conditions and how they are changing over time.

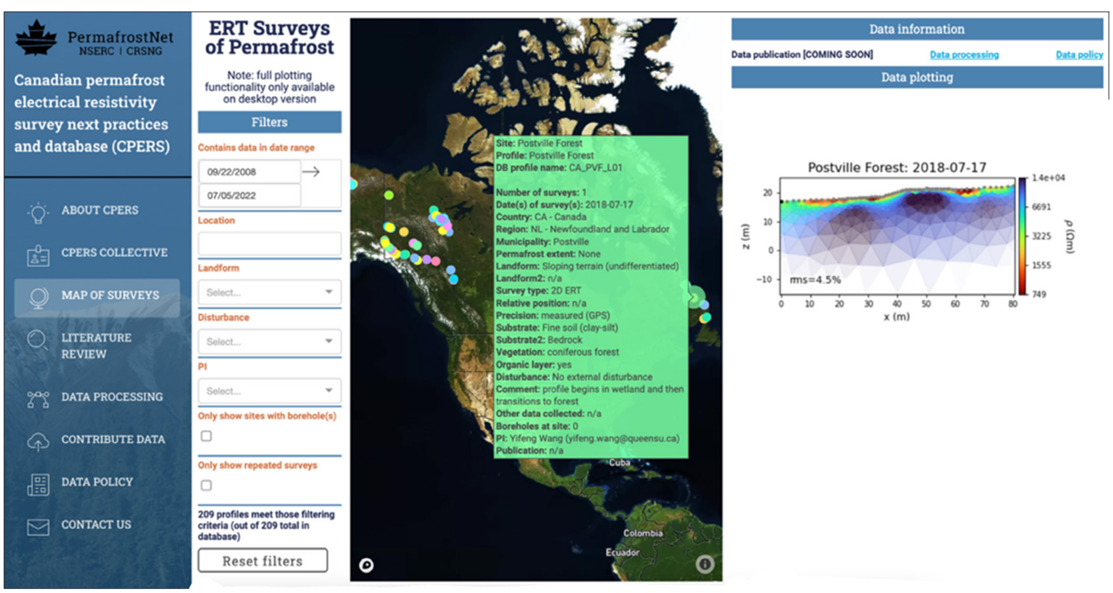


Figure 1. The CPERS website allows users to easily query and visualize ERT surveys of permafrost collected across Canada.

Research summary

Electrical resistivity tomography (ERT) surveys are commonly used to characterize permafrost, but historically, data sharing has been limited. We created and populated the Canadian Permafrost Electrical Resistivity (CPERS), published the data in an established repository to ensure long-term accessibility (CPERS Collective, 2023), and wrote a data paper to promote this resource (Herring et al., n.d.). We also created an interactive web map so data can easily be queried and plotted (https://data.permafrostnet.ca/cpers/). Researchers from the University of Ottawa, Queen's University, and the University of Alberta have already provided data for 280 ERT surveys collected between 2008 and 2022 in British Columbia, Labrador, Northwest Territories, Quebec, Yukon Territory, and Alaska. We used the initial data contributions to make large-scale interpretations of how permafrost conditions across Canada are influenced by mean annual air temperature, landform type, near-surface substrate, and surface disturbance (Herring et al., 2024). We also published a paper describing best practices for ERT surveying of permafrost (Herring et al., 2023) to provide guidance for ERT data acquisition, processing, and interpretation.

Taking action

Data is essential for characterizing permafrost environments and making informed decisions about mitigating and adapting to permafrost thaw. If you would like to contribute data to the CPERS database or learn more about the project, please visit https://data.permafrostnet.ca/cpers/.

Connections to other projects

1 2 This project is directly relevant to **Theme 1** (characterization of permafrost) and **Theme 2** (monitoring of permafrost change).

Partners, team members and support

We gratefully acknowledge Robert Way, Yifeng Wang, Alexandre Chiasson, Joseph Young, and Duane Froese for their data contributions, as well as the data collectors and field assistants, who are too numerous to list here. We thank Nick Brown for the IT support, Etienne Godin for assisting with the Nordicana D data publication, and the Digital Research Alliance of Canada for the digital resources. Greg Oldenborger, Fabrice Calmels, and Anne-Marie Leblanc provided guidance on this project. We thank members of the International Permafrost Association action group "Towards an International Database of Geoelectrical Surveys on Permafrost (IDG-SP)" who collectively developed the metadata form and database structure used for this project.

Acknowledgment, thanks and funding

We gratefully acknowledge the Inuit of Nunatsiavut, Labrador, the Sahtu Dene and Métis of the central Mackenzie valley, Teslin Tlingit Council, Kluane First Nation, White River First Nation, Nacho Nyak Dun First Nation, Kaska Dena First Nation, Tr'ondek Hwëch'in First Nation, Vuntut Gwitchin First Nation, the Nunatsiavut Government, Nunatsiavut Research Centre, NunatuKavut Community Council, and communities of Fort Good Hope, Norman Wells, and Tulita. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and NSERC PermafrostNet.

References

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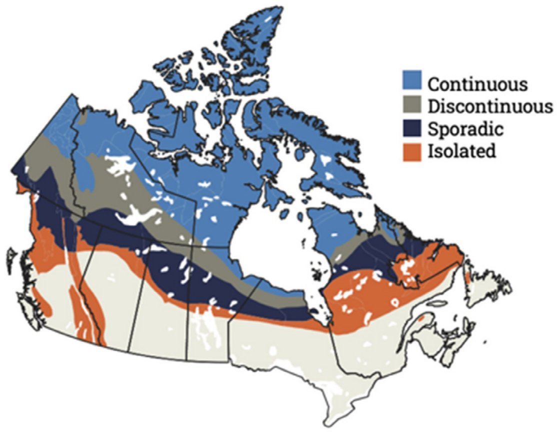
Herring, T., Lewkowicz, A. G., Chiasson, A., Wang, Y., Way, R. G., Young, J. M., Froese, D., Andersen, B., Bellehumeur-Génier, O., Bevington, A. R., Bonnaventure, P. P., Duguay, M. A., Etzelmüller, B., Gooseff, M. N., Godsey, S. E., Miceli, C. M., & Smith, S. L. (n.d.). The Canadian Permafrost Electrical Resistivity Survey Database (CPERS): 15 years of permafrost resistivity data [Manuscript in preparation]. *Arctic Science.*

Herring, T., Lewkowicz, A. G., Way, R. G., Wang, Y., Chiasson, A., & Froese, D. (2024). Large-scale assessment of permafrost conditions using the Canadian Permafrost Electrical Resistivity Survey (CPERS) database [Maniscript submitted to ICOP 2024]. *International Conference on Permafrost.*

Herring, T., Lewkowicz, A., Hauck, C., Hilbich, C., Mollaret, C., Oldenborger, G. A., Uhlemann, S., Farzamian, M., Calmels, F., & Scandroglio, R. (2023). Best practices for using electrical resistivity tomography to investigate permafrost [Manuscript accepted for publication]. *Permafrost and Periglacial Processes.*

Mapping and understanding how ice conditions change in thermokarst lakes over multiple decades.



Maria Shaposhnikova1, Claude Duguay[1] and Pascale Roy-Léveillée[2].
1. University of Waterloo 2. Université Laval

Study locations: Old Crow Flats, northern Yukon.

Keywords: Lake ice, thermokarst lake, lake drainage, satellite, remote sensing, machine learning, neural network.

This research produces maps from a machine-learning algorithm that shows where the ice in shallow lakes is frozen to the bed (bedfast ice) and where it is not (floating ice). The differences in ice conditions impact the stability or thaw of permafrost. The maps can be generated going back 30 years and reveal how fast and where changes are happening. Having such maps helps us understand why changes in environments such as the Old Crow Flats occur and predict how they might continue in the future. The maps can inform local knowledge holders and scientists on how observations at differing locations may be related.

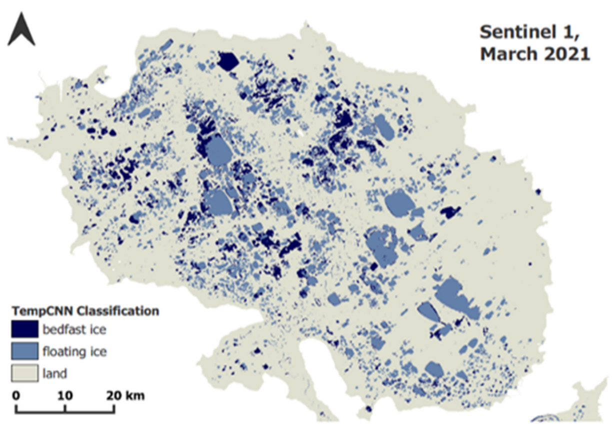


Figure 1 shows a map produced from a machine learning algorithm using a Synthetic Aperture Radar (SAR) image taken by the Sentinel 1 satellite in March 2021. The algorithm has classified the surface as either land, floating ice or bedfast ice. Maps have been produced from 1993 to 2021 and the machine learning algorithm can be applied in other permafrost regions.

Research summary

Lake ice changes in response to climate change. Many shallow Arctic lakes and ponds freeze to bed in the winter months, maintaining the underlying permafrost. As climate changes, fewer lakes are expected to develop bedfast ice, and this can accelerate permafrost thaw. To understand this, we need to know where the ice is bedfast, where it floats, and how these patterns change over time. This research has developed a method for making such maps based on satellite radar images. It produced maps for the Old Crow Flats from 1993 to 2021 that aligned well with field measurements and the Canadian Lake Ice Model. The maps show that the area covered by bedfast ice has increased over the 29 years, which is tentatively attributed to the catastrophic drainage of some lakes, lowered water levels, and a reduction in snowfall in the region.

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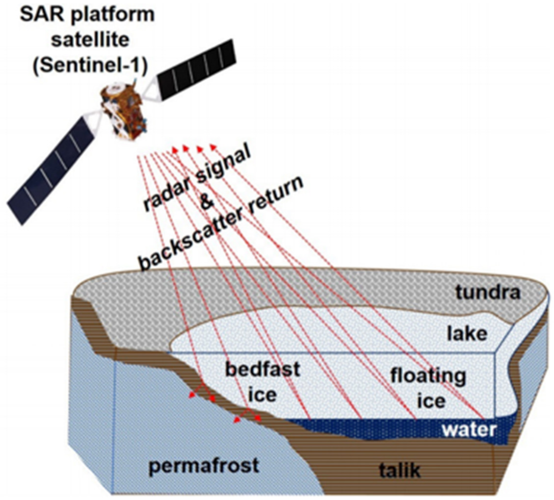


Figure 2 shows the components of tundra and lake landscapes and how a Synthetic Aperture Radar (SAR) satellite can detect the difference between land, floating ice and bedfast ice.

Taking action

he next step for these findings that researchers could follow up on is the simulation of the development of lowland thermokarst. Accurate maps of bedfast ice and lake extent allow for the tracking of lake drainages and early identification of catastrophic drainages and thermokarst events and processes, which scientists can use to predict future changes and also for the local community to employ mitigation and adaptation measures.

Connections to other projects

4 This project links to theme 4 projects also being conducted in Old Crow Flats by Danielle Chiasson, looking at permafrost recovery in drained lakes and ponds, and Nicole Corbiere, looking at mercury and methylmercury concentrations in drained basin complexes in Old Crow Flats, Yukon, Canada.

Regional synthesis

This work provides a strong baseline for future thermokarst lake ice dynamics analysis in the Old Crow Flats and beyond, as thermokarst lowlands cover approximately 20% of the northern permafrost regions and contain significant stores of soil organic carbon.

Documenting transitions between bedfast and floating ice is crucial to understanding permafrost dynamics beneath shallow lakes and drained lake basins, with potential impacts on methane ebullition and the regional carbon balance, in addition to affecting the livelihood of the local community (e.g. fishing, trapping, travelling).

Partners, team members and support

This research benefited from support from Nina Vogt, Louis-Philippe Roy, Caleb Charlie, and Cathy Koot (Yukon University), who collected field data in April 2021, Kevin Turner (Brock University), who provided a vegetation map of Old Crow Flats, and Nastaran Saberi (University of Waterloo) who provided technical support throughout the project.

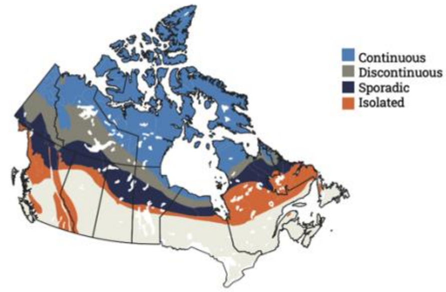
Acknowledgment, thanks and funding

This project recognizes Old Crow Flats as the traditional territory of the Vuntut Gwitchin First Nation and Aklavik First Nation and the Vuntut Gwitchin First Nation land claim agreement. The Old Crow Flats include Vuntut National Park, the Vuntut Gwitchin Category A Settlement Lands, and Special Management Area lands. Thanks go to the Vuntut Gwitchin First Nation and Yukon Government. This work was supported by the Natural Sciences and Engineering Research Council (NSERC) Alexander Graham Bell Canada Graduate Scholarship and NSERC PermafrostNet.

References

Shaposhnikova, M. (2021). Temporal Deep Learning Approach to Bedfast and Floating Thermokarst Lake Ice Mapping using SAR imagery: Old Crow Flats, Yukon, Canada. UWSpace. http://hdl.handle.net/10012/17414

Shaposhnikova, M., Duguay, C., and Roy-Léveillée, P. (2023). Bedfast and floating-ice dynamics of thermokarst lakes using a temporal deep-learning mapping approach: case study of the Old Crow Flats, Yukon, Canada. The Cryosphere, 17, 1697–1721, https://doi.org/10.5194/tc-17-1697-2023.



Fate of carbon in Canadian permafrost-affected soils

Charles Gauthier[1], Joe Melton[2], Oliver Sonnentag[1].
[1]Université de Montréal, [2]Environment and Climate Change Canada
Keywords: Carbon CLASSIC

Study locations: Global, 20 sites

This research has shown us the importance of considering both the quantity of carbon in soils as well as the flux of carbon out of soils when modelling the response of soil carbon to climate change, especially in permafrost soils. This is important because many efforts made to improve models only consider the amount of carbon in soils while paying little attention to fluxes. For example, this research showed that considering fluxes when improving climate models can greatly help narrow down the errors.

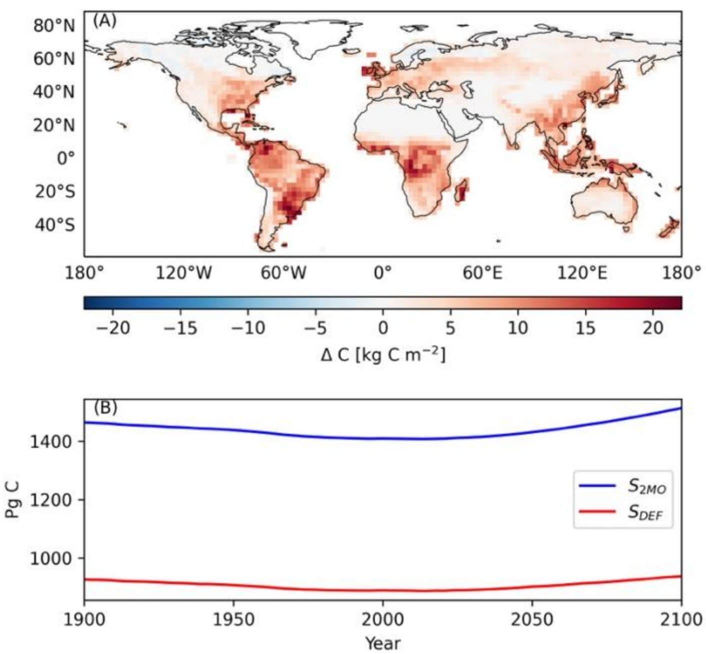


Figure 1. (A) Difference in simulated soil carbon at the end of the century (2100) between CLASSIC using its default parameter values (SDEF) and our optimized parameters (S2MO). (B) Historical and future simulation of global soil carbon stock using the SDEF and S2MO parameter sets. The figure indicates that with the new optimized parameters, CLASSIC predicts an increase of soil carbon globally, with less carbon in high latitude than the default parameterization predicts.

Research summary

Terrestrial biosphere models (TBMs) that are used to simulate the fate of soil organic carbon under climate change contain uncertainty due to poorly constrained parameters. Parameters related to soil carbon are impossible to measure in the field due to the scales at which they operate. Therefore, their value has to be assigned arbitrarily. In this research, we optimized the soil carbon parameters of CLASSIC. To do so, we used a global sensitivity analysis and a Bayesian optimisation framework that used bulk soil carbon data as well as soil respiration data. We were able to generate a parameter set that improved CLASSIC's simulation of high-latitude soil organic carbon and soil respiration. Our results provide the modeling community with an improved soil carbon scheme that can more adequately represent soil carbon dynamics. From those improved parameters, modelers will be able to make better predictions about the fate of soil carbon under climate change.

Taking action

Models such as CLASSIC are crucial tools to deepen our understanding of permafrost thaw and therefore have the potential to play a major role in addressing the issues caused by thawing permafrost. Firstly, permafrost related processes should be included in soil carbon schemes of terrestrial biosphere models. Then, to improve those processes, a wider variety of data should be collected to offer parameter optimization efforts more ways to constrain parameters. Data such as isotopic carbon concentration in soil which are poorly represented in permafrost soil could be part of next data collection campaigns.

Connections to other projects

3

This project received advice and feedback from all members of PermafrostNet theme 3. Additional discussions were held with members of other themes through joint meetings where we had the chance to present and discuss our projects.

Partners, team members and support

This project was supported by NSERC PermafrostNet and by Université de Montréal. Gesa Meyer from ECCC provided useful and critical help in performing the simulations with CLASSIC.

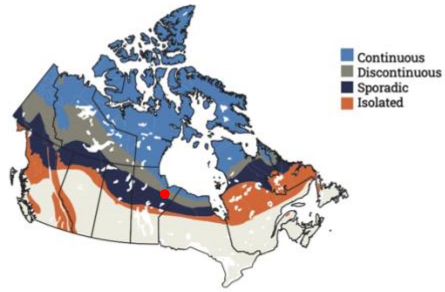
Acknowledgment, thanks and funding

The vast majority of this project was conceived and produced at Université de Montréal which is located on the traditional territory of the Kanien’kehà:ka in Tiohtiá:ke/Montreal. This territory as long been a place of exchange between several First Nations including the Kanien’kehá:ka of the Haudenosaunee Confederacy, Huron/Wendat, Abenaki, and Anishinaabeg. We recognize and respect the Kanien’kehà:ka as the traditional custodians of the lands and waters of this territory. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and NSERC PermafrostNet.

References

Science Borealis Blog article, produced as part of pitch and polish:
https://blog.scienceborealis.ca/why-frozen-mud-is-a-technical-challenge-for-climate-scientists/

A scientific publication is currently in the works and should be submitted to the Journal of Advances in Modeling Earth Systems before the end of the year 2023 for publication in 2024.



Geocells as effective supports for permafrost thaw under railway embankments.

Payam Sharifi[1], *Ryley Beddoe*[1] *and Shawn Kenny*[2]
1. GeoEngineering Centre at Queen's-RMC 2. Carleton University

Keywords: Geocell, linear infrastructure, reinforcement, mitigation, digital image correlation, modelling.

Study locations: Hudson Bay Railway (HBR) corridor, northern Manitoba.

This project found that using geocell reinforcement to reduce lateral deformation is most advantageous when the active layer is between 1-2 m below grade. Similarly, the stability of the embankment was improved up to 50% when using a geocell at the optimal height. The study also found that the stability performance improvement using geocell will gradually diminish over the long term due to increasing dominance from permafrost degradation. This research has shown that the use of geocells in permafrost embankments can provide significant improvements to the design life of the embankment.

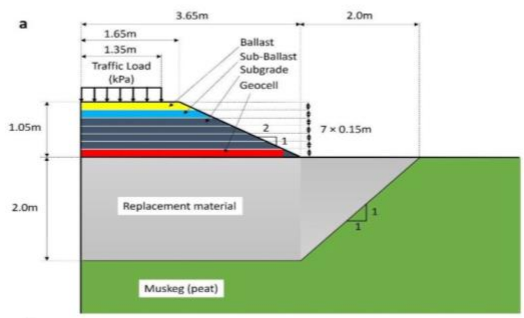


Figure 1.

Figure 1 is a cross-section diagram of a geocell-supported embankment.

Research summary

The Hudson Bay Railway is a rail corridor in Northern Manitoba built across a range of permafrost terrain and peat conditions. Every year the HBR experiences a significant number of deformations and embankment instabilities. Recently, HBR has used geocells, a common reinforcement technique in non-permafrost soils, to improve the support of railway on the degrading permafrost and underlying peat layer. This project looked at thermo, hydro and mechanical processes using finite element analyses to examine and predict thaw deformations, settlement, and stability. To investigate the effectiveness of geocell supports, 2D numerical modeling of the embankment structure with two commercial software (ANSYS and SIGMA/W) were developed. A variety of future scenarios along a typical HBR rail embankment compared with a geocell-supported embankment near Churchill and Gillam were modelled. The modelling developed a better understanding of the contact analysis between the wooden sleepers and soil media and the influence of the suction strength on the stability of embankment (SEEP/W and SLOPE/W). This was combined with a field component including the digital image correlation technique for monitoring track displacement and deformations at locations where the geocell reinforcements have been used.

Taking action

This paragraph provides next steps to address issues caused by thawing permafrost. Provide specific information and actionable steps. Three to four sentences. **Approx. 150-200 words**

Connections to other projects

1 5

This project connects to other projects looking at linear infrastructure in theme 1; *Geomechanical properties of thawing permafrost*, as well as other theme 5 projects; *Sustainable culvert design over degrading permafrost, Hudson Bay railway* and *Risk management of linear infrastructure in remote permafrost terrain: Churchill Railway.*

Partners, team members and support

Thanks to the other team members Pascale Roy-Léveillée, Jocelyn Hayley, James Wilson and Brett Young (Arctic Gateway).
Affiliations: GeoEngineering Centre at Queen's-RMC, Carleton University, NSERC PermafrostNet and ……...

Acknowledgment, thanks and funding

Include a sentence thanking the community /territory who provided assistance.
Include a sentence acknowledging the land and rights holders where this research was located.
This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), NSERC PermafrostNet and [INCLUDE ADDITIONAL FUNDING HERE].
Approx 150 words

References

Include papers, theses or links to other media and information such as data, code or video files that were published from this project.

Partners

University of Alberta
University of Calgary
Carleton University
Laurentian University Université Laurentienne
Université de Montréal
Université Laval
uOttawa
Queen's University
RMC
SFU Simon Fraser University
University of Victoria
University of Waterloo
AWI
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CIRES
Environment and Climate Change Canada
Environnement et Changement climatique Canada
Transports Québec
FCM Federation of Canadian Municipalities
Fédération canadienne des municipalités
Geological Survey Canada 1842 Commission géologique
Nunavut
Northwest Territories
Gwich'in Renewable Resources Board
Inuvialuit Game Council
Lund University
NSIDC
PERMOS
MDA
srk consulting
Standards Council of Canada
Conseil canadien des normes
Tr'ondëk Hwëch'in Hän Nation
YukonCollege
Yukon

Associated Publications

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Acronyms

AEM	Airborne Electromagnetic
AGM	Annual General Meeting
ARI	Aurora Research Institute
ASTD	Atmospheric Science and Technology Directorate (ECCC)
BOD	Board of Directors
BEC	Board Executive Committee
CanESM	Canadian Earth System Model
CCADI	Canadian Consortium for Arctic Data Interoperability
CCS	Government of Nunavut Climate Change Secretariat
CCCS	Canadian Centre for Climate Services (ECCC)
CCMEO	Canada Centre for Mapping and Earth Observation
CIRNAC	Crown-Indigenous Relations and Northern Affairs Canada
CLASSIC	Canadian Land Surface Scheme including Biogeochemical Cycles
CMIP6	Coupled Model Intercomparison Project 6
CNGO	Canada Nunavut Geoscience Office
CNSC	Churchill Northern Studies Centre
CPA	Canadian Permafrost Association
CPERS	Canadian Permafrost Electrical Resistivity Survey
CREATE	NSERC Collaborative Research and Training Experience
CT	Computed Tomography
DEM	Digital Elevation Model
DO	Director of Operations (Network Manager in the proposal)
DOI	Department of Infrastructure, Government of the Northwest Territories
DOI	Digital Object Identifier
EDI	Equity, Diversity and Inclusion

EDIC	Equity, Diversity and Inclusion Committee
ERT	Electrical Resistivity Tomography
ESM	Earth System Model
FCM	Federation of Canadian Municipalities
FIPPA	Freedom of Information and Protection of Privacy Act
FLNROD	Ministry of Forest, Lands, Natural Resource Operations and Rural Development (BC)
FNNND	First Nation of Na Cho Nyak Dun
Fodar™	Foto detection and ranging
GEOBIA	GEographic Object-Based Image Analysis
GRIP	Ground Ice Potential Map
GRRB	Gwich'in Renewable Resources Board
GSC	Geological Survey of Canada
HBL	Hudson Bay Lowlands
HBR	Hudson Bay Railway
HPC	High-Performance Computing
HQP	Highly Qualified People/Person/Personnel (context dependent; also see discussion in Section 7)
IASC	International Arctic Science Committee
IGC	Inuvialuit Game Council
ICCRE	International Conference on Cold Regions Engineering
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association
ITK	Inuit Tapiriit Kanatami
KMCC	Knowledge Mobilization and Communication Committee
KMCCoor	Knowledge Mobilization and Communication co-ordinator
LEAP	Training tomorrow's LEAders in Permafrost thaw and northern research

LiDAR	Light Detection and Ranging
MDA	MacDonald, Dettwiler and Associates Ltd.
MeHg	Methylmercury
MTQ	Ministère des Transports du Québec
NDS	Network Data Scientist
NRA	Northern Research Assistant
NRCan	Natural Resources Canada
NSERC	Natural Sciences and Engineering Research Council
NSIDC	National Snow and Ice Data Center, University of Colorado, USA
NTAI	Northern Transportation Adaptation Initiative (Transport Canada)
NTGS	Northwest Territories Geological Survey
OMNRF	Ontario Ministry of Natural Resources and Forestry
PACS	Permafrost ArChive Science
PCSP	Polar Continental Shelf Program
PCN	Permafrost Carbon Network
PDF	Postdoctoral Research Fellow
PDSP	Permafrost Data Science Platform
PERMOS	Swiss Permafrost Monitoring Network
PFT	Plant functional type (a form of metaspecies)
PI	Principal Investigator
PINGO	Permafrost Information Network of Ground Observations
POLAR	Polar Knowledge Canada
RCOP	Regional Conference on Permafrost
RKI	Infrastructure Canada Research and Knowledge Initiative
RMC	Royal Military College of Canada

RPAS	Remotely Piloted Aircraft Systems
RPAS-SfM	Remotely Piloted Aircraft Systems-Structure-from-Motion
RTS	Retrogressive thaw slump
SAR	Synthetic aperture radar
SC	Scientific Committee
SCC	Standards Council of Canada
SD	Scientific Director (same as PI)
SKOS	Simple Knowledge Organization System
SOPs	Standard Operating Procedures
SRK	SRK Consulting Inc.
TC	Transport Canada
Teams	Microsoft Teams business communication platform
TEB	Transportation Engineering Branch (Yukon Government)
TempCNN	Temporal convolutional neural network
TH	Tr’ondëk Hwëch’in Government
ToR	Terms of Reference
UAV	Unmanned Aerial Vehicle
YGS	Yukon Geological Survey

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