DUE NORTH

FACING THE COSTS OF CLIMATE CHANGE FOR NORTHERN INFRASTRUCTURE

CANADIAN CLIMATE INSTITUTE
L'INSTITUT CLIMATIQUE DU CANADA

JUNE 2022

Arviat, Nunavut. Photo: Dylan Clark.

CONTENTS

ᓯᕗᒧᑦ

ᐅᑭᐅᑦᑕᖅᑐᓕᐊᕐᓇᖅ: ᑲᒪᒋᔭᕆᐊᖃᕐᓂᖅ ᓯᓚᐅᑉ ᐊᓯᙳᖅᐸᓪᓕᐊᓂᖓᓄᑦ ᐊᑭᓕᐅᑎᐅᔭᕆᐊᓕᖕᓂᒃ ᐅᑭᐅᑦᑕᖅᑐᕐᒥ ᓴᓇᔭᐅᓯᒪᔪᓂᒃ ᐱᓕᕆᐊᖃᕐᒪᑕ ᓇᑐᓇᐃᔭᐃᑐᑎᒃ ᖃᓄᐃᓕᐅᕈᑎᐅᔭᕆᐊᓕᖓ ᐃᓄᖕᓄᑦ ᑲᓇᑕᐅᑉ ᐅᑭᐅᑦᑕᖅᑐᖓᓃᑦᑐᓄᑦ ᑭᓯᖃᑦᑎᐊᙱᓗᐊᕐᑎᓪᓗᒥ ᐅᓗᕆᐊᓇᕐᓯᕙᓪᓕᐊᑎᓪᓗᒍ ᓯᓚᐅᑉ ᐊᓯᙳᖅᐸᓪᓕᐊᓂᖓᓄᑦ. ᐅᓇ ᒪᕐᕈᐃᓕᖓᔪᖅ ᐅᓗᕆᐊᓇᕈᑎ ᐊᒃᑐᐃᓂᖃᕐᔪᕐᓂᖓᓂᒃ ᐋᓐᓂᐊᖃᖅᑕᐃᓕᓂᒃᑯᑦ, ᐊᑦᑕᓇᖅᑐᒦᑦᑕᐃᓕᓂᕐᒧᑦ, ᑮᓇᐅᔭᓕᐅᕈᑎᐅᔪᓄᑦ, ᐊᒻᒪ ᐃᓄᐃᑦ ᐃᓕᖅᑯᓯᖓᓂᒃ ᐅᑭᐅᑦᑕᖅᑐᓕᒫᒥᑦ, ᐱᔪᐊᕐᑐᒥ ᓄᓇᖃᖅᑐᖅᑲᕐᓄᑦ ᐃᓄᖕᓄᑦ.

ᐅᓂᒃᑳᓕᐅᕐᓂᕐᒧᑦ ᑎᑎᕋᖅᑎᒋᔭᐅᔪᑦ ᓄᓇᖃᖅᓯᒪᔪᑦ ᐊᒻᒪᓗ ᐃᖅᑲᓇᐃᔭᕐᓯᒪᔪᑦ ᑲᓇᑕᐅᑉ ᐅᑭᐅᑦᑕᖅᑐᖓᓂᒃ ᑭᓯᐊᓂᓕ ᓇᓕᐊᒃ ᐅᑭᐅᑦᑕᖅᑐᕐᒥᐅᑕᐅᙱᑦᑐᖅ. ᓄᓇᖅᑲᖅᑳᖅᓯᒪᓇᑕᓗ.ᑐᑭᓯᕚᓪᓕᐊᕐᓗᑎ ᐱᕐᑯᑎᒋᔭᐅᔭᕆᐊᓖᑦ ᐃᓪᓗᐃᑦ ᐊᔾᔨᒋᙱᓪᒪᒋᑦ ᐅᑭᐅᑦᑕᖅᑐᕐᒥᐅᓄᑦ, ᐅᔾᔨᕆᓂᕐᓴᐅᕙᓪᓕᐊᑎᓪᓗᑕ ᑖᓐᓇ ᐅᕐᑲᐅᓯᐅᔪᖅ ᓇᖕᒥᓂᖅ ᐅᓂᒃᑳᓕᐊᕆᔭᐅᔭᕆᐊᖃᕐᓂᖓᓂᒃ ᓴᓂᑦᑎᐊᖓᒍᑦ *ᐃᒪᐅᑉ ᐃᓗᐊᓂ: ᓯᓚᐅᑉ ᐊᓯᙳᖅᐸᓪᓕᐊᓂᖓᓄᑦ ᐊᑭᓕᐅᑎᐅᔭᕆᐊᓕᖕᓂᒃ ᓯᓚᐅᑉ ᐊᓯᙳᖅᐸᓪᓕᐊᓂᖓᓄᑦ ᑲᓇᑕᐅᑉ ᐱᖁᑎᖏᓐᓂᒃ*.ᐱᒻᒪᕆᐊᓘᓚᐅᕐᒪᓐ ᐅᕙᑦᑎᓐᓄ ᓄᓇᖅᑲᖅᑳᖅᑐᑦ ᑎᒍᒥᐊᖅᑎᐅᓂᖏᓐᓂᒃ ᐅᑭᐅᑦᑕᖅᑐᕐᒥ ᐃᓚᒋᔭᐅᑎᑕᐅᓗᓂ ᐅᕙᓂ ᖃᐅᔨᓴᕐᓂᕐᒥᒃ ᐱᕙᓪᓕᐊᑎᑦᑎᔾᔪᑎᐅᓂᑯᓂᒃ ᑕᒪᐃᓐᓂ ᓄᓇᖅᑲᖅᑳᖅᑐᑦ ᐱᓇᓯᐊᖅᑕᕆᓐᓂ ᐊᒻᒪᓗ ᐊᑐᖅᑕᐅᔪᓐᓇᕐᓴᔾᑐᓂᒃ ᐱᕐᑎᓄᑦ ᐋᖅᑭᒋᐊᕈᑎᐅᔪᓐᓇᕐᓴᕐᑐᓂᒃ ᐱᓕᕆᐊᕐᓂᕐᒧ.

ᐱᓕᕆᐊᒃᑎᖃᕐᓯᒪᓚᐅᖅᑕ ᐅᖃᐅᓯᐅᑉ ᓄᓇᖅᑲᖅᑳᖅᑐᑦ ᐱᔪᓐᓇᐅᑎᖏᓐᓂᒃ ᑎᒍᒥᐊᖅᑎᐅᔪᓂᒃ ᐊᒻᒪ ᐅᑭᐅᑦᑕᖅᑐᕐᒥ ᐃᑲᔫᑎᖃᖅᑎᑦᑎᔾᔪᑎᐅᔪᓂᒃ ᐊᕐᕿᑰᓕᖅᑐᓂᒃ ᒪᕐᕿᓐᓂ ᑐᕋᓪᓚᖅᑐᑎᒃ ᐊᑐᕈᓐᓇᖅᑐᒃᑯᑦ ᐃᓱᒪᒋᔭᖏᓐᓂᒃ ᖃᐅᔨᔭᖏᓐᓂᓪᓗ ᐊᒻᒪ ᐱᐊᓂᒍᑎᒋᔭᖏᓐᓂᒃ ᐊᒻᒪᓗ ᐃᓱᒪᓕᐊᕆᔭᖏᓐᓂᒃ ᐅᓂᒃᑳᓕᐅᕈᒪᓪᓗᑎᒃ.ᑐᓴᐅᒪᑎᑦᑎᓂᒃᑯᑦ ᐊᑐᕐᓯᒪᔭᖏᓐᓂᒃ, ᖃᐅᔨᒪᔭᖏᓐᓂᓪᓗ ᐊᒻᒪ ᐱᓕᕆᐊᖃᓚᐅᕐᓂᖏᓐᓄᑦ, ᐱᔪᓐᓇᐅᑎᓂᒃ ᑎᒍᒥᐊᖅᑎᐅᔪ ᐊᒻᒪ ᐃᑲᔫᑎᖃᖅᑎᑦᑎᔾᔪᑎᐅᔪᑦ ᐅᕙᑦᑎᓐᓂ ᐃᑲᔪᓚᐅᕐᑐᑦ ᐋᖅᑭᒃᓯᐅᕙᓪᓕᐊᓂᕐᒥᒃ ᑐᑭᓯᒃᑲᓐᓂᕈᑎᓂᒃ ᒫᓇ ᐅᑭᐅᑦᑕᖅᑐᕐᒥ ᐱᕐᑎᕆᔭᐅᔪᑦ ᐊᑯᑦᑐᔫᑎᐅᓂᖏᓐᓂᒃ ᐊᒻᒪᓗ ᐊᒃᑐᐃᔾᔪᑎᒃᑲᓂᐅᔪᓐᓇᖅᑐᓂᒃ ᓯᓚ ᐅᖅᑰᓯᕙᓪᓕᐊᓂᖓᓄᑦ.

ᖃᐅᔨᒪᔪᒧᑦ ᑐᓵᔭᓇᓚᐅᕐᓂᕗᑦ ᐱᒋᐊᕈᑎᑐᐃᓐᓇᐅᓂᖓᓂᒃ, ᑭᓯᐊᓂᓕ ᖃᐅᔨᒪᔪᒧᑦ ᐅᓄᒃᑲᓐᓂᖅᑐᐊᓗᖕᓂ ᐅᓂᒃᑳᓂ ᑐᓴᕆᐊᕐᓂᑦᑎᓐᓂᒃ.ᐅᒃᐱᕈᓱᒃᑲᑦᑕ ᐱᓪᓚᕆᐅᓂᖓᓂᒃ ᑕᒪᒃᑯᐊ ᓚᕙᒪᓕᕆᓂᒃᑯᑦ ᖃᓄᐃᓕᐅᕈᑎᐅᔪᑦ ᓄᓇᖅᑲᖅᑳᖅᑐᑦ ᓚᕙᒪᖓᓂᒃ ᐅᖃᖅᑕᖅᑲᖅᑐᑎᒃ ᑐᑭᓯᓯᒪᔭᓇᕐᓂᐊᕐᒪᑕ ᐱᕐᑎᓄᑦ ᖃᓄᐃᓕᐅᕈᑎᐅᔭᕆᐊᖅᑐᑦ ᓄᓇᓕᖕᓂ ᐊᒻᒪᓗ ᐱᓕᕆᖅᑎᕉᓐᓂᒃᑯᑦ ᐋᖅᑭᒃᓯᐃᓗᑎᒃ ᑕᒪᒃᑯᓄᖓ ᐋᖅᑭᒃᓯᔾᔪᑎᒃᓴᓂᒃ.

Ndòo

Dii Gwits'at: Nanh Gwiniik'òo diinagòo'ee ejùk t'eenjaa jii zheh, taii, vik'iighè' aadrii, Geenjit gwidaatł'oo tr'igwinah'ii nits'òo goo'aii gatr'igwaandak Canada Nanh Gwiniik'òo gwiiyeendoo diinagòo'ee ejùk t'eenjaa gwik'iighè' jii zheh, taii, vik'iighè' aadrii, diits'atgwighàa t'igwįį'ee neesrigwiją̀ hch'uh.Jii neekaii gwizhit srii gwandàih, gwiizuu ch'i', nits'oo tr'igwindaii ts'àt diinigwįį'ee Nanh Gwiniik'òo gwideetoh tthak, iisrits'at Dinjii Zhuh, Ineekaii, Teenjir Nilii kat.

Canada Nanh Gwiniik'òo, gwideetoh jii juudìn kat gwidinehtł'èe' gidinuutł'oo guulàt Canada Nanh Gwiniik'òo t'igiinch'ù' ts'àt gwitr'it t'igugwah'inh, gòo ihłee Nanh Gwiniik'òo gwits'at iidilii kwaa.Dinjii Zhuh, Ineekaii, Teenjir Nilii kat gàa iidilii kwaa.Gwiiyeendoo srits'àt gah'iidindaii zheh, taii, vik'iighè' aadrii iisrits'àt ejùk Nanh Gwiniik'òo Gwidinji' Kat guuveenjit diits'atgwighàa go'aii, gwiiyeendoo ts'àt gwinaa'ii jii gwizhit tr'igįįkhii khè' gwidinehtł'èe' jii gwinjik *Chuu T'eh: Jii diinagòo'ee ejùk t'eenjaa Canada kat zheh, taii, vik'iighè' aadrii geenjit gwidaatł'oo.* Dinjii Zhuh, Ineekaii, Teenjir Nilii kat gwiiyeendoo guuchidhaa'ee dàgwìdįį'e' zhit Jii Nanh Gwiniik'oo guk'andehtr'inahtii gwizhit giteelyaa jii Dinjii Zhuh, Ineekaii, Teenjir Nilii kat kheenjit-niint'aii tr'iheelyaa ts'àt gwiiyeendoo gwiniint'aii ts'àt jii zheh, taii, vik'iighè' aadrii gwits'àt tr'itr'heendal.

Dinjii Zhuh, Ineekaii, Teenjir Nilii kat leii dàgwìdįį'e' Kat ts'àt Nanh Gwiniik'òo Gwidinji' Kat gwizhit giinlii ts'àt khaii neekaii gwinòo gwizhit guuvah jii gwidinehtł'èe' nihkhaa Geenjit gwitr'it tr'igwiłtsaii łọọhàh agidanh gah'iidindaii gwizhit, gwichiilagoo'dhat leii, ts'àt dagwiheedya'aa gwiiniidhan.Jii nihts'àt nihtatr'ìndaii nihk'it tr'igwindaii zhit, gahtr'idandaii, ts'àt łọọhàh iisrits'àt gahdandaii, jii Kat dàgwìdįį'e' giinlii ts'àt juudìn kat gwizhit giinlii kat nikhwits'àt gwitr'it hàh tr'iginiinjik ts'àt guuk'iighè' gwiiyeendoo gah'iidindaii jii jùk Nanh Gwiniik'òo jii zheh, taii, vik'iighè' aadrii gwitł'at ts'àt nanh gwiniidhaa hàh nihłi'ejùk diinagòo'ee ejùk t'igwinjih.

Gah'iidindaii oodhidhaacheii gwiitsał gwidik gwizrih, gòo, tth'aih hèe gwindàk leii tr'ehdeetth'ak go'aii.Akòo gwik'iinjiidizhit adachoo nihłi'ejùk gwizhit kat tthak nihkhaa nihts'àt nit'soo go'aii gahtr'idandaii eenjit Dinjii Zhuh, Ineekaii, Teenjir Nilii adachoo kat hàh jii zheh, taii, vik'iighè' aadrii diits'atgwighàa dagoonch'uu kaiik'it leii gwa'an ts'àt nihkhah' geenjit gwitr'it gwiinzii t'ugugwah'ah'aa.

nîkanasinahikêwin

kîwêtinohk-isi: kâ-mâmîskowîpahk ôma kîwêtinohk atoskêwin ôma kitâpahtamok ôma kîwêtinohk mâna kâ-wîkihk kânata môya mâna mistahi kâ-ayâhk wâwêyis ôma kâ-mâmiskociwîpahk mâna ôma.nîso ôhi mitoni pakamiskâkowak mitho-mâcihôwinihk, mithowâthawinihk, atoskîwinihk, îkwa nîhithawîwinihk-isi ôtî kîwîtinohk, wâwêyis ithiniwak.

kîyâm âta âtiht ôki omasinahikîwak kî-wîkowak mîna kî-âtoskîwak misiwî-kîwîtiohk kânata, môtha ohci kîcinâc kîwîtinohk.môtha mîna nîyinân ithiniwak.athîwâk ôma kâ-âti-nanistohtamâhk ôma kâ-isi-athiman ôma ohci ithiniwak ohci kîwîtinohk, nawac mâci-nistohtînân ôma ka-pîyak astîk mâsinahikan kotak mîna *atâmipêhk: tânisi kâ-itakîhtêk ôma kâ-mâmîskociwîpahk ohci kânata.* poko mîna ka-sohkastêk ôma ôki ohci ithiniwak kathâtihk kîwîtinohk kâ-ôcîcik mîna ka-akimihcik ôma kâ-wî-nanitonikêhk îkotî nawâc ithiniwak ka-nohkôtâwak ôma ka-paminisotwâw îkwa ka-miskwîtamâsowak ôhi ohci nîkânihk kâwî-nakiskâkik.

mîscît âsay pîkiskwîhâwak ôki ithiniwak îkwa kîwîtinohk ohci âsay ôtî nîso-askiya ôhi osâm môtha î-nôhtî-patahamihk kîkiway mîna kahkiyaw ka-pîtâkosit asithiniw ôma masinahikan, pîkiskwîwina îkwa tânisi î-isi-nitawihtamihk.kîpsin ôma ka-wîthamihk, nanistohtamowin, îkwa askiy pimohtîwin, ôki kâkî-mîkositwâw ôma askiy îkota ka-wîcihitâwak athiwâk nanistohtamowin ôma kâ-wîkihk kîwîtinohk îkwa kîkway î-manîsihk kîspin ôma athiwâk kâwî-mâmîkociwîpahk.

nikiskithinân ôma môtha mistahi ôma kâ-kiskîthitamâhk, mâka, mistahi âcimowina îtakona ôtê nîkân. nitâpowakîthinân ôma ôki kahkiyaw onîkânîwak poko ka-wîtapimâtwâw nîhithaw-onîkânîwak ka-nistohtâkik kîkwaya ôhi kâ-manîsitwâw îkwa mîna poko ka-mâmawi-atoskâtahkik ôhi ka-mitho-pathik kîkway.

Foreword

Due North: Facing the costs of climate change for Northern infrastructure seeks to describe the challenges that people in Northern Canada face with inadequate infrastructure under increasing threat from climate change. This twin threat impacts the health, safety, livelihoods, and cultures of people across the North, particularly Indigenous people.

Although some of the report's authors have lived and worked across Northern Canada, none of us are Northerners. Nor are we Indigenous. The more we came to understand the unique infrastructure challenges facing Northerners, the more we realized that the subject required its own dedicated report alongside *Under Water: The costs of climate change for Canada's infrastructure*. It was important to us that Indigenous people as rights holders in the North be included in this research in a way that advanced both Indigenous self-determination and durable solutions to infrastructure challenges.

We have actively engaged with many Indigenous rights holders and Northern stakeholders over the past two years with the goal of meaningfully amplifying their perspectives in this report's findings, conclusions, and recommendations. By sharing their lived experiences, knowledge, and expertise, these rights holders and stakeholders helped us develop a more thorough understanding of the existing Northern infrastructure gap and the added impacts of a warming climate.

We acknowledge that our listening efforts have only scratched the surface, however, and that there are many more stories that need to be heard. We believe it is essential that all orders of government engage directly with Indigenous governments to understand the infrastructure challenges communities are experiencing and collaboratively develop the needed solutions.

Pond Inlet, Nunavut. Photo: Dylan Clark.

ACKNOWLEDGMENTS

Authors

Dylan G. Clark, Senior Research Associate, Canadian Climate Institute

Dena Coffman, Research Associate, Canadian Climate Institute

Ryan Ness, Adaptation Director, Canadian Climate Institute

Isabelle Bujold, Research Assistant, Canadian Climate Institute

Dale Beugin, Vice President Research, Canadian Climate Institute

Adaptation Expert Panel Report Working Group

Ashlee Cunsolo, Founding Dean, School of Arctic and Subarctic Studies, Labrador Campus of Memorial University

Brian Horton, Manager, Climate Change Research, Yukon University

Ian Mauro, Executive Director, Prairie Climate Centre

Deborah McGregor, Canada Research Chair, Indigenous Environmental Justice, York University

Enooyaq Sudlovenick, PhD Candidate, University of Manitoba

External Reviewers

Colleen Healey, Principal, Sijja Consulting, City of Iqaluit, Nunavut

Antoni Lewkowicz, Professor Emeritus, Department of Geography, Environment and Geomatics University of Ottawa

Steve Roddick, Senior Analyst, Resilient North Consulting; Former City Councillor, City of Whitehorse, Yukon

Consultant Research Team

Knut Kitching, Firelight Group

Jordan Tam, Firelight Group

Catherine Baxendale, Firelight Group

Rachel Olsen, Firelight Group

Brent Boehlert, Industrial Economics, Inc.

James Neumann, Industrial Economics, Inc.

Jason Price, Industrial Economics, Inc.

Charles Fant, Industrial Economics, Inc.

Paul Chinowsky, Resilient Analytics and University of Colorado at Boulder

Jacob Helman, Resilient Analytics

Aurora Marstokk, Navius Research

Jotham Peters, Navius Research

Tosh Southwick, IRP Consulting

This work would not have been possible without the time and knowledge of the individuals that participated in interviews led by Firelight Group.

Production Support

Design and layout: Laurie Barnett, Graphic Designer

Information design by Voilà: chezVoila.com

Translation: Edgar

Cover design: Alex Wittholz

Photos: Bird's Eye Inc.

Disclaimer: This report is the outcome of a collaborative process involving staff and Expert Panelists from the Canadian Climate Institute, external reviewers, and engaged rights holders and stakeholders. It does not necessarily reflect the views of the individuals or organizations that provided input. Any errors in this report are attributable to the Institute.

Recommended citation: Clark, Dylan G., Dena Coffman, Ryan Ness, Isabelle Bujold, and Dale Beugin. 2022. *Due North: Facing the costs of climate change for Northern infrastructure*. Canadian Climate Institute. Ottawa, ON.

This project was undertaken with the financial support of:

Environment and Climate Change Canada — Environnement et Changement climatique Canada

Arviat, Nunavut. Photo: Dylan Clark.

EXECUTIVE SUMMARY

Northern Canada faces a double threat of already-inadequate infrastructure in a rapidly warming climate. *Due North*, the first major assessment of the costs of climate change to infrastructure across all of Northern Canada, finds that all orders of government should set policies and make investments without delay to prepare for the impacts of climate change on Northern infrastructure.

Despite infrastructure's crucial role in the North, the region already faces a significant infrastructure gap. Inadequate infrastructure is a threat to health, well-being, and livelihoods across the North—particularly for Indigenous People. Housing insecurity is worse in the North than anywhere else in Canada. Most Northern communities rely on diesel generators for electricity and do not have reliable high-speed internet. Advanced medical care frequently requires a flight to southern Canada, and prices for food and other goods can be two to five times higher than in southern Canada because of poor transportation infrastructure.

As if these challenges weren't enough, the climate in Northern Canada is warming three times faster than the global average. The resulting permafrost thaw, more frequent and damaging extreme weather, and unpredictable snow and ice conditions are amplifying existing Northern infrastructure problems, with devastating consequences for Northerners.

Over the past two years, the Canadian Climate Institute has been working, with input from Northern rights holders, governments, and other stakeholders, to identify the costs of climate change impacts to Northern infrastructure. Due North documents the findings of our analysis, including:

- The first ever permafrost thaw projections for the entire North and estimates of the cost of damage for Northern infrastructure
- Projections of winter road viability
- First-hand accounts of the social and cultural impacts of climate-related infrastructure failure and disrepair

- Estimates of the costs and benefits of both incremental and transformative adaptation measures to prevent or delay the impacts of climate change

Infrastructure damage from permafrost thaw across Northern Canada—Yukon, Northwest Territories, Nunavut, Nunavik, and Nunatsiavut, as well as the northern regions of British Columbia, Alberta, Saskatchewan, Manitoba, and Ontario—is increasing rapidly. Runways, roads, and building foundations will sustain significant damage from permafrost thaw, winter roads will become more unsafe and less viable during warmer winters, and sea level rise and floods will threaten the viability of some communities.

Our analysis shows that early investments in infrastructure adaptation can reduce costs and prevent disruption of essential services. However, incremental adaptations alone won't be sufficient—the effects of climate change are only exacerbating decades, if not centuries, of poor planning, underinvestment, and neglect. Developing infrastructure for the future of the North will require transformative adaptations as well as incremental adaptations. In many cases, this will mean following the lead of Northerners to reimagine the way that infrastructure services are delivered and support education and community knowledge-sharing networks.

We recommend four types of actions that can not only reduce climate change costs and impacts on Northern infrastructure but can also lay a path to more functional, appropriate, and resilient infrastructure.

- **FUNDING:** The federal government should dedicate new financial resources for Northern infrastructure and should restructure existing infrastructure funding programs to increase accessibility and usefulness to Northern governments.
- **INFORMATION:** The federal government should support provincial, territorial, and Indigenous governments in developing and maintaining accurate and practical information about Northern-relevant climate risks to infrastructure. This data should prioritize information that is important to Northern decision makers and Indigenous communities.
- **INNOVATION:** All orders of government should prioritize infrastructure replacement and transformative leapfrogging over repair and protection wherever this is found to be a more effective, efficient, and sustainable way to safeguard services.
- **REGULATION:** Federal, provincial, and territorial governments should update infrastructure policies, regulations, standards, and codes to explicitly account for the more complex and severe impacts of climate change in the North and to ensure that new infrastructure is resilient.

Because colonization and racism are among the root causes of climate change infrastructure vulnerability, the four recommendations are rooted in a guiding principle of self-determination: All infrastructure development and adaptation policies should be implemented in a manner that is consistent with the principles outlined in Canada's Truth and Reconciliation Report. By working with Indigenous Peoples through a process of partnership and equal collaboration, federal, provincial, and territorial governments have an opportunity to fundamentally rethink the way infrastructure is built in the North to better serve the needs of Indigenous Peoples.

Russia's February 2022 invasion of Ukraine brought significant attention to questions of Northern security and national defence. Defence investments and policies resulting from these concerns have the potential to address pre-existing threats and build Northern resilience; however, unless Canada learns from mistakes of the past, such policies could also exacerbate North-south infrastructure inequities, disempower Indigenous Peoples, and increase vulnerability to climate change. Our analysis underscores the centrality of infrastructure and climate adaptation in any assessment of the threats facing the North.

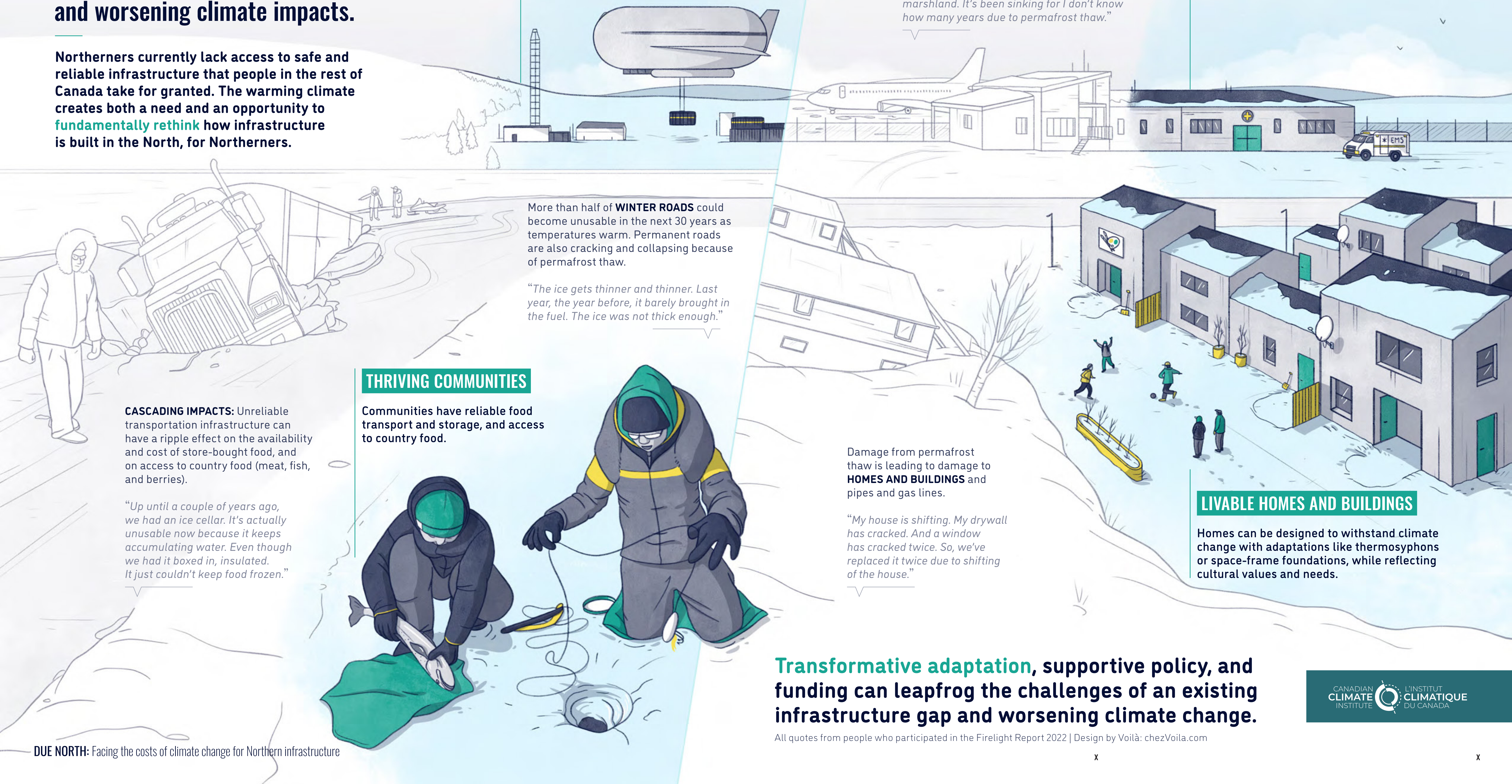
For too long, reliable, functional, and high-quality infrastructure has been unavailable for many Northerners. With the climate changing faster in Northern Canada than anywhere else in North America, the challenge is only growing. All orders of government must act to help transform Northern infrastructure—from inadequate and vulnerable to appropriate and resilient—to help Northerners secure a safe, healthy, and prosperous future.

Groswater Bay, Nunatsiavut. Photo: Bird's Eye Inc.

Transformative adaptation

is needed to address the Northern infrastructure gap and worsening climate impacts.

Northerners currently lack access to safe and reliable infrastructure that people in the rest of Canada take for granted. The warming climate creates both a need and an opportunity to fundamentally rethink how infrastructure is built in the North, for Northerners.



SAFE AND RELIABLE TRANSPORT

Transport systems can be reimagined to move supplies to where Northerners need them, even in an environment that is constantly shifting because of climate change impacts.

RUNWAYS are warping and cracking due to permafrost thaw and extreme weather. When permafrost erodes, runways can lose the ability to support an airplane's weight.

"Here's the runway... And this entire area is marshland. It's been sinking for I don't know how many years due to permafrost thaw."

DEPENDABLE AIRPORTS

Airports can be designed to operate in the changing environment and better support reliable delivery of health services and supplies.

More than half of **WINTER ROADS** could become unusable in the next 30 years as temperatures warm. Permanent roads are also cracking and collapsing because of permafrost thaw.

"The ice gets thinner and thinner. Last year, the year before, it barely brought in the fuel. The ice was not thick enough."

THRIVING COMMUNITIES

Communities have reliable food transport and storage, and access to country food.

CASCADING IMPACTS: Unreliable transportation infrastructure can have a ripple effect on the availability and cost of store-bought food, and on access to country food (meat, fish, and berries).

"Up until a couple of years ago, we had an ice cellar. It's actually unusable now because it keeps accumulating water. Even though we had it boxed in, insulated. It just couldn't keep food frozen."

Damage from permafrost thaw is leading to damage to **HOMES AND BUILDINGS** and pipes and gas lines.

"My house is shifting. My drywall has cracked. And a window has cracked twice. So, we've replaced it twice due to shifting of the house."

LIVABLE HOMES AND BUILDINGS

Homes can be designed to withstand climate change with adaptations like thermosyphons or space-frame foundations, while reflecting cultural values and needs.

Transformative adaptation, supportive policy, and funding can leapfrog the challenges of an existing infrastructure gap and worsening climate change.

All quotes from people who participated in the Firelight Report 2022 | Design by Voilà: chezVoila.com

CANADIAN CLIMATE INSTITUTE | L'INSTITUT CLIMATIQUE DU CANADA

Our ongoing research into the costs of climate change includes the following reports:

2020

TIP OF THE ICEBERG
FALL 2020

If we think of the costs of climate change as an iceberg ahead, this introductory paper zooms in on the tip of the iceberg—the known and measurable hazards—as well as the contours of what lies below the water.

THE HEALTH COSTS OF CLIMATE CHANGE
SPRING 2021

A closer look at health costs and adaptation opportunities, built around our analysis of the costs of heat-linked health burdens, Lyme disease, and air quality changes. The report includes a discussion of mental health impacts and other difficult-to-quantify health costs.

UNDER WATER
FALL 2021

A focused analysis on infrastructure costs and adaptation opportunities, built around our modelling of climate-induced impacts to flooding, transportation infrastructure, and electricity systems.

DUE NORTH
SPRING 2022

An analysis of the poor condition of Northern infrastructure, how it's putting communities at risk, and the need to advance policies and investments to better serve Northerners and prepare the region's infrastructure for the effects of climate change.

MACROECONOMIC
FALL 2022

Using national macroeconomic modelling of potential climate change impacts to vulnerable sectors and assets, this report will outline the implications of a changing climate on economic productivity and well-being.

2023

Pangnirtung, Nunavut. Photo: Dylan Clark.

1

INTRODUCTION

Infrastructure in Northern Canada is not just a vital part of daily life for Northerners, including Inuit, First Nations, and Métis—it can be a matter of life and death. In spite of infrastructure's crucial role in the North, however, the region faces a significant infrastructure gap. And with Northern Canada warming at three times the global average due to accelerating climate change, the consequences for Northern infrastructure and those who depend on it could be severe.

Preparing and repairing Northern infrastructure for the accelerating impacts of climate change is a pressing challenge for Northern, Indigenous, and federal governments. There are three major barriers to ensuring resilient infrastructure services across Northern Canada:

1. **As a result of the Northern infrastructure gap, existing infrastructure across the North is consistently failing to serve the most basic needs of Northerners.** Northerners do not have access to the same quality of infrastructure services as other people in Canada. For example, housing insecurity is higher in Northern Canada than anywhere else in the country; most Northerners lack dependable health and transportation infrastructure; and many communities do not have access to high-speed internet.

2. **Despite the cultural strength and resilience of the North's many Indigenous Peoples, a legacy of racist and colonial harms continues to impede efforts to prepare for and adapt to climate change** (Ford et al. 2015; Ready and Collings 2020). Historically, governments designed social and economic policies to contain and destroy Indigenous knowledge and cultures (Truth and Reconciliation Commission of Canada 2015). To this day, crucial infrastructure decisions continue to be made in Ottawa without meaningful input and direction from Northern Indigenous Peoples.

3. **Climate change in the North is happening faster and having a greater impact than in the rest of Canada.** In the past 50 years, the average global temperature has increased by 0.8 degrees Celsius. In that time, Canada's average temperature has risen 1.7 C—and the

North has warmed by 2.3 C, roughly triple the rate of the global average (Bush and Lemmen 2019). Furthermore, the North faces unique climate-related hazards such as permafrost thaw and changes to sea ice conditions that could have devastating effects on Northern communities and livelihoods.

This report is part of the Canadian Climate Institute's Costs of Climate Change series, which seeks to quantify and assess some of the biggest costs of climate change across Canada, including to infrastructure. Because of the urgent and unique challenges posed by climate change in Northern Canada, this report specifically addresses the impacts and costs for Northern infrastructure, building off of our 2021 report *Under Water*, which assesses the threats to infrastructure in Canada more broadly. This report focuses on climate change infrastructure impacts unique to the North, such as the effects of permafrost thaw on roads, airports, homes, and buildings.

Our analysis finds that Northern infrastructure—and as a result, Northerners—are highly exposed and vulnerable to climate-related hazards. Impacts will vary across the North. Some places are already experiencing infrastructure damage and costs from permafrost thaw. Other places that are further North, with cooler climates, may have more time to prepare but may also experience the most dramatic change in the long term.

For some types of infrastructure, such as buildings and runways, retrofitting and replacing infrastructure can delay or reduce costs and damages, ensuring that Northerners continue to have access to essential services. But even with significant global emissions reductions and adaptive measures to protect infrastructure, some existing Northern infrastructure may not be possible or practical to maintain over the long term and will have to be reimagined.

As a result, Northern adaptation should emphasize replacement of the infrastructure that is not practical to maintain with new technologies or approaches that are more durable and environmentally sustainable. Federal, provincial, and territorial governments will need to work closely with Northerners and Northern Indigenous governments to reimagine climate-resilient infrastructure that supports long-term well-being, prosperity, and self-determination.

Russia's February 2022 invasion of Ukraine and the increased attention it has brought to questions of Canadian security and national defence only add urgency to addressing the issues this analysis raises. Defence investments and policies have the potential to help address the Northern infrastructure gap and build Northern resilience to the rapidly changing climate, but they could also exacerbate North-south infrastructure inequities, disempowerment of Indigenous Peoples, and vulnerability to climate change. Our analysis highlights the pitfalls and opportunities that are at stake.

The remainder of this report is structured as follows:

- **SECTION 2** addresses the context for this study, including the state of Northern infrastructure, the anticipated consequences of climate change, the role of adaptation, and the colonial foundations of Northern infrastructure.
- **SECTION 3** describes our methodology, which uses climate and infrastructure models to estimate the damage and costs caused by a changing climate and the bene-

fits of adaptation. It also includes descriptive interviews with Northerners, which provide a more complete picture of the implications of infrastructure damage and of actions that are being taken or should be taken to adapt (Firelight 2022).

- **SECTIONS 4 TO 7** present the findings of our analysis for each principal infrastructure type (roads, airports, and homes and buildings) and highlight the voices of Northern Indigenous Peoples, and Northern decision makers.
- **SECTION 8** summarizes our conclusions regarding how climate change may continue to impact the North, describes opportunities to reduce climate-related impacts through adaptation, and recommends policies and actions that can make Northern infrastructure more resilient to the ongoing impacts of climate change.

Arviat, Nunavut. Photo: Dylan Clark.

2

CONTEXT

In this report, we define *the North* as Yukon, Northwest Territories, Nunavut, Nunavik (Quebec), and Nunatsiavut (Newfoundland and Labrador), as well as the northern regions of British Columbia, Alberta, Saskatchewan, Manitoba, and Ontario (Figure 1). This follows the definition used by the Arctic and Northern Policy Framework (CIRNAC 2019). When applicable, we use the term *Inuit Nunangat*, which refers to the four Inuit regions in Canada: Nunavut, Nunavik, Nunatsiavut, and the Inuvialuit Settlement Region. However, we recognize that there are many definitions of the North, that Northern cultures and ecosystems are diverse, and that Indigenous Nations and histories transcend colonial borders (Table 1).

Figure 1

The North

In this report, we define Northern Canada as all regions north of 55 degrees latitude. Nearly 50 per cent of this area is comprised of Inuit Nunangat, which is crosshatched on this map.

Table 1

Population of the North

Category / Territories	Yukon	NWT	Nunavut	Nunavik	Nunatsiavut	Northern regions of provinces west of Quebec
Population 2016	35,874	41,786	35,944	13,188	3,189	404,743
Total number of communities	16	31	25	14	5	54
Number of fly-in communities	1	14	25	14	5	8

The importance of infrastructure in the North

As it does elsewhere in Canada, infrastructure provides many essential services across the North, from housing vital to people's safety, to roads and trails, to functional water and electricity systems. When infrastructure is damaged, destroyed, or in need of repair, communities go without vital services; trade and economic activity are interrupted; and human health is put in jeopardy.

But the consequences of infrastructure failure are often far greater in Northern Canada (Huot et al. 2019). If a water treatment plant or an electrical plant fails in a Northern community, there is seldom a backup system (Office of the Auditor General of Canada 2017; ITK 2020; Sohns et al. 2019). When Northern infrastructure fails, it can quickly lead to life-threatening situations (Funston 2014). Winter and all-season roads, for example, are essential means of accessing medical care, food, and fuel for many communities. Unlike road networks in southern Canada, the Northern communities that are accessible by road typically only have one road leading in and out. This means that an emergency road closure due to a landslide, fire, flood, or washout can quickly cascade to food shortages at grocery stores, medical emergencies with no access to care, and dwindling fuel supplies.

Northern infrastructure systems are deeply interconnected. When one piece of infrastructure fails, it can have cascading effects on other systems. For example, airports require more than just an airplane and a runway to operate safely—they need electricity for lights, access roads for people and supplies, and fuel that is often shipped into the community. An electrical outage or road disruption can create significant problems for the normal operations of an airport in the North. For example, in 2015, a fire destroyed the only power plant in Pangnirtung, Nunavut, and the short runway prevented aircraft from bringing in backup generators (CBC 2015).

Sixty-eight communities across the North can only be reached by air year-round, and many other Northern communities rely heavily on air travel for emergency medical care, food, and essential supplies. Most Northern airports consist of one gravel runway and do not have the required equipment for planes to land when there are crosswinds or poor visibility (Debortoli et al. 2019). Even the technicians needed to fix critical infrastructure may face challenges accessing the community (Clark and Kanduth 2022).

Because most Northern communities do not have a physician or an advanced medical centre, residents rely on airplanes to access medical care in most emergencies (Young et al. 2016). When an airport is not functioning because of a storm, power outage, or runway damage, a community often loses access to advanced life support. Because of poor weather-monitoring equipment at airports, 29 per cent of emergency medical transport has been delayed or cancelled in recent years (Office of the Auditor General of Canada 2017). Airports are also essential to bring physicians to communities for clinics and to transport medical supplies such as blood products. Some residents in the North can use telehealth without having to leave their communities, but slow, expensive, and unreliable internet limits access.

Homes and buildings play an enhanced role in Northern communities. Due to a shortage of safe and affordable housing in the North, one home may house multiple generations of a family. Furthermore, a substantial proportion of residents in the North live in non-market housing (see Box A for discussion).

Non-residential buildings in Northern communities also frequently serve multiple vital roles. For example, in addition to their primary role, school buildings frequently serve as community gathering places or emergency shelters because they are often the largest buildings in town. Buildings are also critical for the delivery of health care to multiple communities in the North. The few hospitals that are above 55 degrees North are in regional hubs like Whitehorse, Yellowknife, and Iqaluit. These regional health hubs serve huge catchments with little or no redundancy in the event of damage or loss of access. If these buildings become uninhabitable or unusable because of the impacts from permafrost thaw, flooding, or other disasters, large numbers of Northerners could be left many hours of air travel from a doctor or hospital.

Whale Cove, Nunavut. Photo: Dylan Clark.

BOX A

Arviat, Nunavut. Photo: Dylan Clark.

Governments have unique roles and responsibilities when it comes to Northern infrastructure

Each order of government plays different roles in infrastructure development and maintenance in Northern Canada than in southern Canada. These differences in the governance and financing of infrastructure are important when considering future costs as well as adaptation policies. Below we outline key roles that each order of government tends to have for airport, roads, and buildings.

THE GOVERNMENT OF CANADA

finances a greater share of infrastructure across Northern Canada than it does in southern Canada. While only two airports in Northern Canada are owned by the federal government (Churchill and Kuujjuaq), federal funding is required to maintain functional and safe airports across the North (see airport funding Box D). Federal financing—through the Canadian Mortgage and Housing Association—is also essential for public housing across the North. Only 13 per cent of Canadian renter households nationwide live in public housing. But in Nunavut, the portion is 84 per cent; in Northwest Territories, 41 per cent; and in Yukon, 25 per cent (Statistics Canada 2017). In some cases (Northern regions of provinces), Indigenous Services Canada provides some housing for First Nations governed by the Indian Act. As in southern Canada, the federal government generally provides substantial financing of highways in the North.

PROVINCIAL GOVERNMENTS

finance and maintain airports, housing, and roads across Northern regions. About 30 airports across the North are owned and operated by provincial governments, most of them in Saskatchewan, Manitoba, and Newfoundland and Labrador. Development of social housing is generally approached the same way from north to south within each province. However, legislation and land claim agreements in Nunavik (Quebec) and Nunatsiavut (Newfoundland and Labrador) delegate additional responsibility to the respective provinces to provide housing. Roads are also managed similarly north to south in each province, though municipalities in Northern regions are generally less involved in road construction and maintenance.

TERRITORIAL GOVERNMENTS

own and operate most airports across Yukon, Northwest Territories, and Nunavut, and own and maintain most roads. Territorial housing corporations develop and maintain most social housing in the territories.

INDIGENOUS AND REGIONAL GOVERNMENTS

are, in some cases, major proponents in the development and maintenance of large infrastructure. For example, as outlined in the James Bay Agreement, the Kitivik Regional Government (Nunavik) is charged with the operation and management of airports and roads across the region. Some self-governing First Nations in Yukon manage social housing programs, like the Kwanlin Dün First Nation Market Housing Program.

MUNICIPAL AND HAMLET GOVERNMENTS

in Northern Canada tend to be less involved in infrastructure development and management than large municipalities in southern Canada. However, municipal and hamlet governments still serve vital functions in maintaining roads and airports across the region. Several airports located in northern regions of provinces are owned and operated by municipalities or local airport authorities. Municipalities also play a key role in land-use planning decisions that impact housing affordability and cost.

Pond Inlet, Nunavut. Photo: Dylan Clark.

The Northern infrastructure gap

Generations of infrastructure plans imposed on the North with narrow goals and limited funding have created a significant Northern infrastructure gap. This gap negatively impacts the lives, livelihoods, health, and well-being of Northerners. With the North facing the accelerated threat of warming at three times the global average, its already-inadequate infrastructure will suffer unique and potentially devastating challenges if the gap is not addressed in ways that account for this rapid and dramatic climate change.

Northern communities do not have the same quality of infrastructure and access to essential services as other Canadians (NAEDB 2016). This gap impacts every major type of infrastructure:

- **HOUSING:** Throughout the North, inflated costs of construction and transportation, a short building season, high population growth, and extreme poverty rates have exacerbated housing shortages. In Nunavut, more than half of all households are overcrowded—defined as each occupant not having their own bedroom—compared to a national average of less than ten per cent (Statistics Canada 2017). Overcrowded and inadequate housing has serious health implications for residents—rates of tuberculosis, for example, are 300 times higher among Inuit than among non-Indigenous people in Canada (Vachon et al. 2018; Patterson et al. 2018). Inadequate housing is also harmful to other aspects of well-being, including personal safety and mental health (Kilabuk et al. 2019; ITK 2019).
- **DRINKING WATER:** Eighty per cent of communities in Inuit Nunangat have no access to piped water and rely on trucked water (ITK 2020). Trucked water is vulnerable to weather conditions and delays and can become contaminated during the transportation process. For instance, in Igloolik, after water trucks failed to sufficiently filter the drinking water, residents endured a boil water advisory after finding parasites in their water (CBC News 2015). In Clyde River, when the water treatment plant broke down, the community's two water trucks could not meet demand for water. The incident caused water shortages that forced the closure of the school and health centre (Lochead 2021).
- **TELECOMMUNICATIONS:** As of 2019, no households in Yukon, Northwest Territories, or Nunavut had access to broadband internet that met the federal government's universal speed target. In comparison, over 90 per cent of households in British Columbia and Quebec had access to broadband that met the speed target (CRTC 2020). In Nunavut, the digital divide is particularly acute: the fastest available internet service—15 megabits per second—is eight times slower than the Canadian average (ITK 2021).
- **ENERGY:** Not a single community in Nunavut, Nunavik, or Nunatsiavut, and only one in four communities in Northwest Territories, are connected to a regional electricity grid (NTI 2020; Karanasios and Parker 2017). Most of these off-grid communities rely on diesel generators, which are costly, loud, and generate substantial greenhouse gas emissions. The average homeowner in Northern Ontario pays an energy bill more than double that of the average Canadian household (Lovekin

and Heerema 2019). Reliance on diesel generators leaves communities without emergency backups, so inclement weather or shipping delays can leave households without heat and electricity.

- **MARINE TRANSPORT:** Sealifts are an essential means of transporting goods, non-perishable food, and fuel to many Northern communities. Currently there are no deep-water ports in the North, although one is under construction in Iqaluit (Transport Canada 2022b). The lack of port infrastructure limits the access of northern communities and businesses to less expensive food, goods, and transport.
- **AIRPORTS:** Air travel is the only reliable, year-round mode of transport for about half of the communities in the North (Government of Canada 2021), yet many Northern airports lack adequate lighting systems for low visibility conditions, which are essential for pilots to land safely in the dark or in inclement weather (Office of the Auditor General of Canada 2017). In Nunavut, runways are on average less than half the length of runways at commercial airports in southern Canada, and most runways are unpaved, allowing only smaller aircraft to safely land (NTI 2020). Smaller planes cannot travel as far or carry as much weight as larger aircraft, limiting transport of critical supplies to remote communities.

The Northern Infrastructure gap is widening as old infrastructure is retired and demand continues to increase because of rapid population growth in the North. From 2006 to 2016, the Inuit population in Inuit Nunangat grew at a rate of 29 per cent—almost three times that of the Canadian population (ITK 2018).

Dramatically inferior infrastructure is not an inevitable result of Northern settlement. Other circumpolar countries face similar challenges for infrastructure development—extreme cold, short building seasons, small populations spread out over large areas—but have sustained a higher quality of infrastructure and more reliable services. Some important examples:

- **TELECOMMUNICATIONS:** Communities in other Northern countries are connected to faster and more reliable services such as fibre optic networks. Alaska's average broadband speed, though the slowest in the United States, is still faster than the fastest available speed in Nunavut (NTI 2020). In 2009, the Danish government laid fibre optic cables across the ocean floor to Greenland—as a result, 93 per cent of the population in Greenland now has access to high-speed broadband (ITK 2021).
- **ENERGY:** Other circumpolar states are transitioning away from diesel generation in remote Northern communities to make energy more reliable, clean, and affordable. For example, the state of Alaska has spent more than US$250 million over the past decade investing in renewable-powered microgrids (Lovekin et al. 2016). Greenland has five hydropower plants that produce 60-70 per cent of its energy (Mortensen et al. 2017).
- **MARINE TRANSPORT:** Without deep-water ports it is more challenging to unload fuel and supplies at each community. Other circumpolar countries like Russia, Greenland, Finland, and Norway all have deep-water ports that serve their Northern communities (Lasserre 2022).

The colonial foundations of Northern infrastructure

Infrastructure in Northern Canada must be understood as the product of Northern history, geography, cultural contexts, and disputes over sovereignty and self-determination. Historically, infrastructure in the North was developed to support colonial expansion and resource extraction, not to serve the needs of Indigenous Peoples who have lived across the North since time immemorial (Cruikshank 1985; Castillo et al. 2020). The story of infrastructure development across the region is in many ways a tale of colonial expansion and racism (LaDuke and Cowen 2020; Baijius and Patrick 2019). Roads, airports, and ports in the North were largely developed by settlers and southern governments to support economic development and national security, while Indigenous Peoples were forcibly relocated to settlements with substandard infrastructure that did not provide for their physical or cultural needs (Figure 2).

The legacy of racist and colonial harm lives on through the absence of sufficient and appropriate infrastructure across Northern Canada. Even today, a lack of sufficient medical facilities means Northerners—particularly Indigenous Peoples—often must leave their communities for extended periods for any advanced medical treatment, including giving birth (Truth and Reconciliation Commission of Canada 2015b), insufficient medical facilities in Northern communities have meant that residents have had to travel south to receive care.

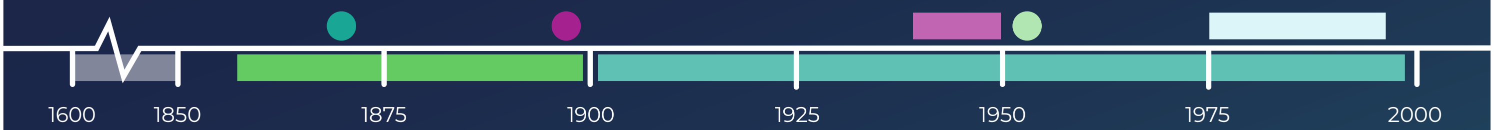
To this day, Indigenous governments and communities have little control over infrastructure decisions across the North. Instead, these decisions are often made by federal, territorial, and provincial governments. This lack of control and agency over infrastructure decisions means that development of new infrastructure in the North does not necessarily serve the needs of the North—a fatal flaw that must be addressed if the threat of climate change to Northern infrastructure is to be successfully met.

Pangnirtung, Nunavut. Photo: Dylan Clark.

Figure 2

Important events in the history of colonial infrastructure development in Northern Canada

Beginning with the arrival of Europeans in the 17th century, settlement and economic development in what is now known as Northern Canada have ignored, exploited, or actively persecuted Indigenous Peoples and cultures. Land claim settlements have begun to return decision-making power to Indigenous communities, but the impacts of centuries of disempowerment, colonialism, and racism continue to this day—including inadequate infrastructure and inequitable decision-making processes.



1600-1850 (approximately)

European explorers arrive in the North, followed by whalers, missionaries, and fur traders. These encounters have profound impacts on Indigenous Peoples, but there is no co-ordinated presence or interest in the North from imperial powers; many communities remain self-governing on their traditional land.

1869

The Hudson's Bay Company sells Rupert's Land to the British Crown, which then cedes it to Canada. This transaction includes parts of southern Nunavut, northern Ontario, Quebec, Manitoba, and Saskatchewan.

1896

Gold is discovered in Yukon, prompting the Klondike Gold Rush and the subsequent formation of Yukon Territory in 1898. White settlers flock to the territory, and infrastructure such as roads and rail are quickly developed to support them. But after the Gold Rush bust around 1905, development stalls for decades, leaving Indigenous communities without critical infrastructure (Morse 2003).

1860s-1900

Commercial whalers set up year-round posts in the eastern Arctic (some of which are still hamlets and towns across the region), decimating marine mammal populations and causing widespread food insecurity and starvation among Inuit.

Early 1900s-1990s

Residential schools are used to forcibly assimilate Indigenous children. In the North, the residential school system arrives later than in the south. Residential schools in the south are widespread by 1900, but don't reach the Eastern Arctic until the 1950s (Truth and Reconciliation Commission of Canada 2015a).

1940s

Before the Second World War, there were no major roads in Yukon and approximately 5,000 people lived in the territory, about half of whom were Indigenous. In 1942, soldiers arrived in Yukon to build the Alaskan Highway in support of the war efforts. By 1944, more than 34,000 men were working on the road in Yukon, Alaska, and northern British Columbia. The population of Yukon's capital, Whitehorse, grew from less than 1,000 to 20,000 in a few months (Cruikshank 1985). Many Indigenous people found employment during this boom, but most of it was short-term.

The number of students attending day schools also increased as new schools were constructed in highway settlements. From 1942 to 1949, the number of schools in Yukon quadrupled and the number of Indigenous students increased by eight-fold (Cruikshank 1985). Once Indigenous children were integrated into the territorial school system, parents who wanted their children to live at home while they attended school had to move to settlements where schools were located.

1953

Inuit from Inukjuak in Northern Quebec are forcibly relocated to Ellesmere and Cornwallis Islands—an effort by the Canadian government to assert sovereignty and establish a presence in the North during the Cold War. Relocated families are not adequately supported and infrastructure remains inadequate 70 years later (Qikiqtani Inuit Association 2014).

1975-1993

A series of Northern land claim agreements are signed, including the James Bay and Northern Quebec Agreement (1975), Yukon Umbrella Final Agreement (1992), and Nunavut Land Claim Agreement (1993). These land claims mark a major step for Indigenous self-determination and rights to the land. Some of the agreements lay out financial compensation for the exchange of land or for resource development, and some establish co-governance structures. Other land claim agreements give Indigenous governments ownership or decision-making power over infrastructure development and maintenance.

"The federal government in 1949 told the 'savages' that they should become civilized—we shall turn them into civilized human beings, rather than being 'savages'... Because of those issues, I'm worried about my grandchildren and my great-grandchildren. I have four great-grandchildren, and I'm worried about their livelihood.... The understanding of the land... is starting to disappear."

—Nunavut participant (Firelight 2022)

Arviat, Nunavut. Photo: Dylan Clark.

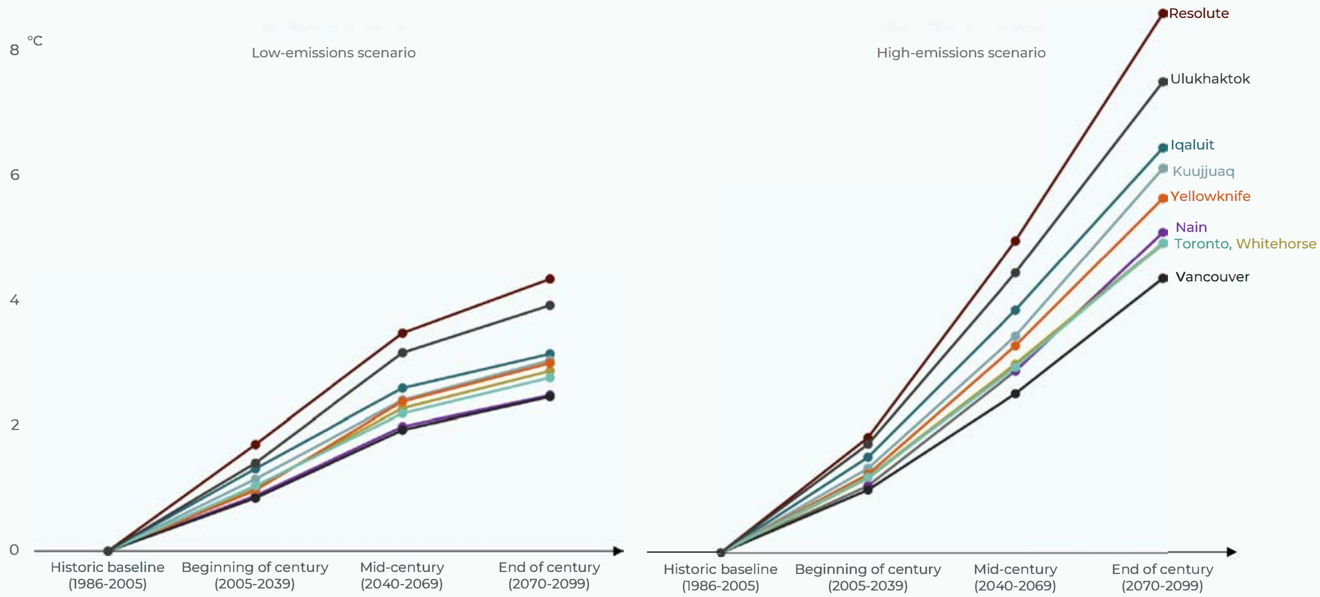
Climate change across the North

Climate change is having more rapid and dramatic impacts in the North than it is in the rest of Canada (Bush and Lemmen 2019). Climate models project an average temperature increase across southern Canada, which is warming much faster than the global average, of 2.2 to 3.1 degrees Celsius by mid-century, and 2.8 to 5.4 C by the end of the century compared to the reference period of 1986-2005. Temperatures across Northern Canada are projected to increase even faster than in southern Canada, with an increase of 2.7 to 3.9 C by mid-century and 3.5 to 6.7 C by end of the century (Figure 3). By the year 2100, many Northern communities could see an increase in annual temperatures of 7 C above the recent average if current emissions trends continue.

Figure 3

Temperatures are rising faster across Northern Canada

Projected average annual temperature increases for cities in southern and Northern Canada



Source: Data was obtained from the Canadian Centre for Climate Services and is based on an ensemble of 27 global climate model projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5). In this figure, each line reflects the projected changes in average annual temperature with respect to the reference period of 1986-2005.

> "Right now, here we are in October 14th and normally we have snow here, but now it's just sunshine and plus eight right now. We haven't had any snow here at all, and normally it freeze up here on the lake."
>
> —*Northwest Territories participant (Firelight 2022)*

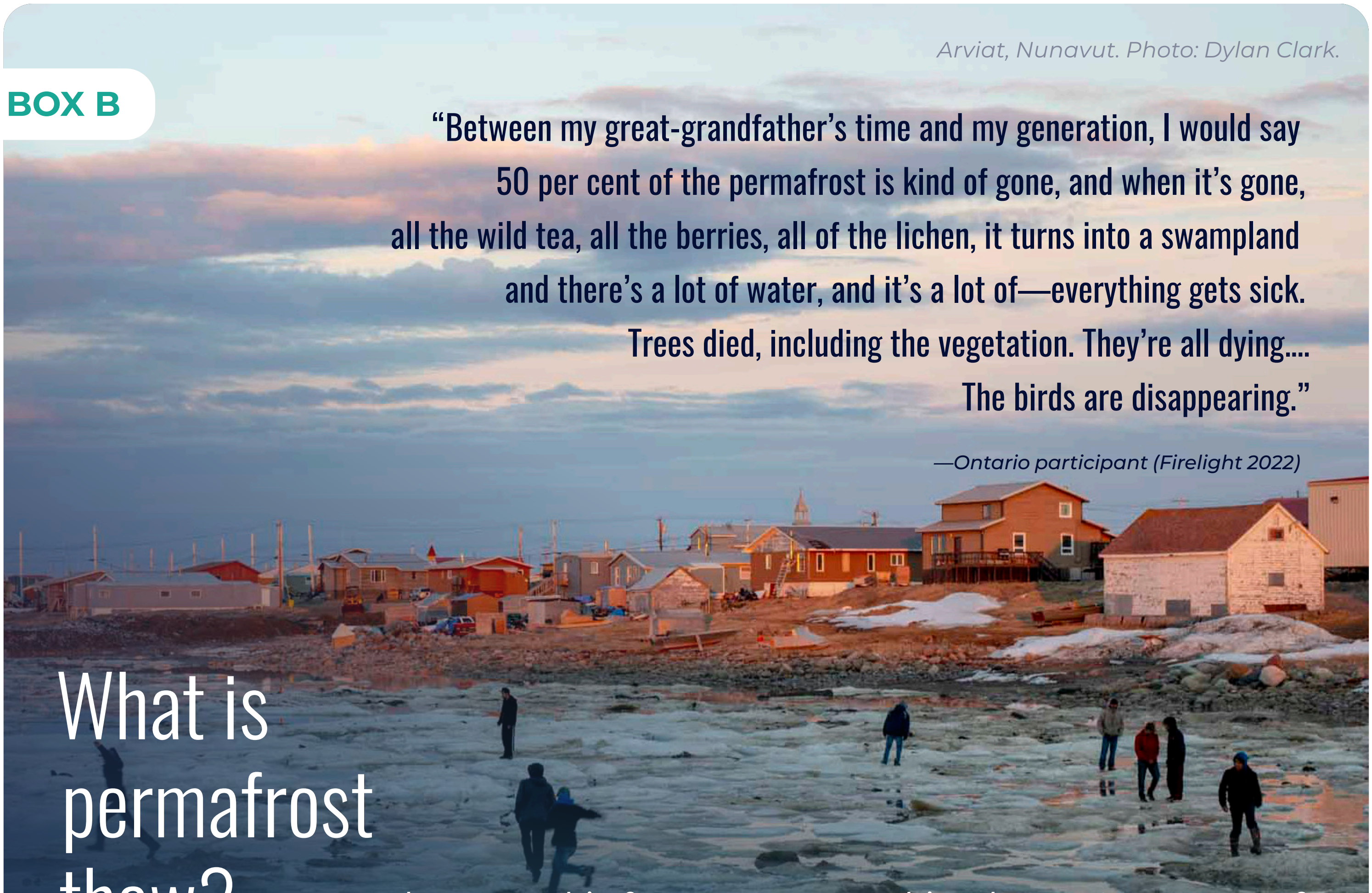
Dawson City, Yukon

Arviat, Nunavut. Photo: Dylan Clark.

Rising temperatures are also causing major shifts in the weather and environment of the North, such as increases in extreme snow and rain (Streicker 2016). Indigenous Elders and Knowledge Holders have been observing many of these changes for decades (Ford et al. 2018; Simonee et al. 2021). They have described unprecedented shifts in weather patterns, such as dramatic or sudden changes in wind direction, melting sea ice, and changes to plants and wildlife (Huntington et al. 2017; Gearheard et al. 2011; Streicker 2016; Arctic Council 2016).

Weather extremes are also shifting quickly across the North (Underwood and Bertazzon 2020). For example, thunderstorms, which have historically been uncommon or non-existent in the high North, have become regular occurrences over the past decade (Holzworth et al. 2021). The increase in thunderstorms and lightning strikes is likely to contribute to additional wildfires in the Arctic (Masrur et al. 2018; Chen et al. 2021).

Slower-onset impacts of climate change are also changing the landscape of the North. Permafrost is thawing quickly across the North, bringing new hazards (see Box B). Rising sea levels and sea ice loss are increasingly eroding and flooding coastal settlements, while relative sea levels are falling in other locations due to isostatic rebound, rendering ports unusable (Underwood and Bertazzon 2020). These changes in weather extremes as well as slower-onset shifts are causing damage to infrastructure, making travel more dangerous, and altering the relevance of some Indigenous Traditional Knowledge, which is highly place-based (Hjort et al. 2018).



Arviat, Nunavut. Photo: Dylan Clark.

BOX B

> "Between my great-grandfather's time and my generation, I would say 50 per cent of the permafrost is kind of gone, and when it's gone, all the wild tea, all the berries, all of the lichen, it turns into a swampland and there's a lot of water, and it's a lot of—everything gets sick. Trees died, including the vegetation. They're all dying.... The birds are disappearing."
>
> *—Ontario participant (Firelight 2022)*

What is permafrost thaw?

The ground is frozen year-round in about 50 per cent of Northern Canada (about 2.5 million square kilometres). This frozen ground is called permafrost, and in some places, it extends hundreds of metres below the surface and is as cold as -15 degrees Celsius. However, as temperatures warm and the amount of rain increases, Arctic permafrost is increasingly thawing.

When permafrost thaws, the soil, gravel, and sand that was once frozen solid can start to shift, slump, and slide (Radosavljevic et al. 2016; AMAP 2019). This can significantly damage roads, buildings, airports, and other infrastructure, which were often built on the permafrost as a natural foundation. When permafrost thaws beneath a building, the floors and walls can shift and crack, roads may develop sink holes or become extremely uneven, and runways can lose the ability to withstand an airplane's weight (Melvin et al. 2016; Vogt 2021). In addition to the direct impacts on infrastructure and communities, permafrost thaw will also profoundly disrupt Northern ecosystems and landscapes, with dramatic impacts to people who harvest and travel on the land.

Adapting and preparing for climate change in the North

Under both low- and high-emissions scenarios, accumulated greenhouse gases in the atmosphere will continue to change the climate in the North for decades to come (Figure 3). Protecting Northern infrastructure from climate change impacts will therefore require not just reducing emissions but also adaptation, to safeguard Northern infrastructure services from climate-related hazards, as part of broader efforts to bolster resilience to future climate impacts.

Climate change adaptation refers to actions that help to prevent or reduce climate change impacts and leverage any benefits of a changing climate (IPCC 2022; Smit et al. 2000). Adapting to current and future climate-related hazards is essential in order to protect people, communities, and livelihoods across Canada.

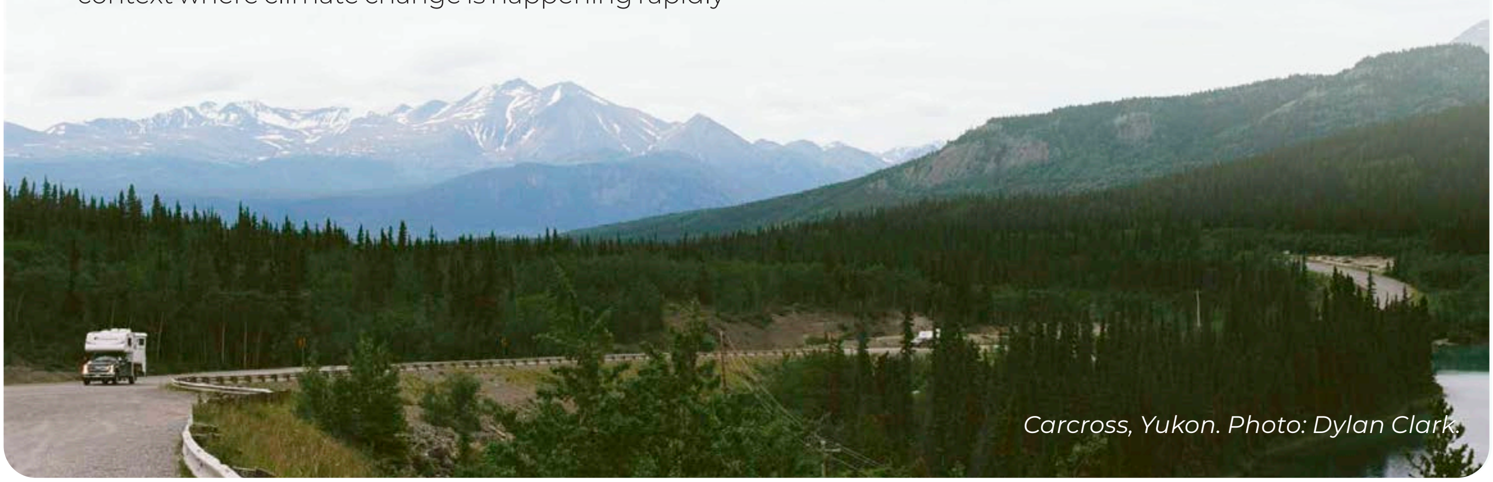
Adaptation can include a range of options, from ***incremental adaptations*** to more ***transformative adaptations*** (Kates et al. 2012). Incremental adaptations aim to protect and preserve existing infrastructure systems. Transformative adaptations, on the other hand, focus on the delivery of services, rethinking what infrastructure and social systems are required to best meet the goals. Adaptation choices are especially important in the Northern context where climate change is happening rapidly and infrastructure is already deficient. Choosing the wrong path could result in both wasted resources and perpetuating vulnerabilities.

In the context of Northern infrastructure, examples of incremental adaptations include:

- Using engineering practices to reinforce and protect infrastructure to slow damage from permafrost thaw
- Applying methods of passive cooling to prevent or slow permafrost thaw
- Updating building codes and standards to ensure that new infrastructure is designed for future climate risks
- Developing processes for monitoring and evaluating infrastructure to make climate-informed repair and replacement decisions

Examples of transformative adaptations include:

- Relocating infrastructure to more stable terrain
- Reimagining the way that infrastructure services are delivered
- Supporting education and community knowledge-sharing networks to build awareness of climate hazards



Carcross, Yukon. Photo: Dylan Clark.

3

METHODS

Our research consists of four components. The first three involve modelling the damages and costs associated with permafrost thaw impacts on airports, permafrost thaw and temperature impacts on permanent and winter roads, and permafrost thaw impacts on buildings. The fourth component presents stories and knowledge shared through interviews with Indigenous people living across the North to increase understanding of the consequences of infrastructure damage from permafrost thaw and other climate change impacts to Indigenous cultures, livelihoods, and well-being.

Climate change is increasing the risks of infrastructure damage and service disruption across the North. The damage and costs associated with some of these risks can be estimated, as we have done with the impacts to infrastructure that we have considered in this report. However, some risks can only be identified and described, but cannot yet be modelled or projected (Figure 4). There may well be other risks that are still unknown.

Double Mer, Nunatsiavut: The body of water in front of the snowmobile is usually fully frozen in April; in 2021 the ice melted extremely early. Photo: Bird's Eye Inc.

Figure 4

Known and unknown infrastructure impacts in Canada: the climate costs iceberg

A growing body of academic research is beginning to shed light on these risks, but it may never be possible to completely understand all climate change impacts. Considering this uncertainty, infrastructure adaptation choices need to build resilience to a wide range of potential futures and be flexible and adaptive to changing conditions. It is important to note that in many cases risks are better understood through Indigenous knowledge systems or through local knowledge than with western science. Information in this figure is from Streicker 2016; Arctic Council 2016; Ford et al. 2018; Bush and Lemmen 2019.

RISKS TO NORTHERN CANADA for which we can start to calculate the scale of impact and cost

- Damage to buildings, roads, and airports across the North from permafrost thaw
- Reduction of winter road season or complete loss of winter roads
- Increased frequency and severity of floods in some regions

CLIMATE IMPACTS THAT COULD AFFECT THE NORTH but the scope and scale are not well understood

- Impacts on Indigenous ways of life, culture, and knowledge from irreversible changes to land-scapes and ecosystems
- Sea level rise and coastal erosion impacts to coastal communities
- Increased risk of landslides due to permafrost thaw
- Larger and more frequent lightning, tornados, and heatwaves
- More frequent and widespread wildfires
- Impacts to health from disruption of health-care services, degraded housing quality, and food insecurity

RISKS THAT MAY HAVE MAJOR IMPACTS through complex interactions and processes and that are very challenging to predict

- Increased commercial and military marine traffic through Northern Canada due to sea ice retreat
- Climate change-induced disruptions to national and international supply chains, causing scarcity and price increases for food and fuel
- Cascading failures across interconnected infra-structure systems, such as the impacts of a shorter winter road season on fuel delivery

Modelling impacts and costs

To determine the focus of our analysis, we talked to Northern stakeholders and rights holders and reviewed the literature about the importance of different types of infrastructure across the North and the potential threats posed by climate change. Based on importance to Northerners, strength of evidence connecting climate change with economic costs, and the availability of data, we chose three key infrastructure types—airports, permanent and winter roads, and homes and buildings. We recognize that these are not the only important types of infrastructure in the North that are vulnerable to climate change, but because we have the right data and tools to analyze airports, roads, and buildings, we can provide an important window into the challenges climate change poses for Northern infrastructure.

To model the impacts of climate change on infrastructure, we needed to understand what Canada's future climate might look like. Studies of climate change impacts typically draw on global climate models that project future shifts in the climate caused by global greenhouse gas emissions. Such models do not provide a single picture of the future climate under changing emissions levels, but rather a range of possible futures reflecting the complexity of the global climate system and the uncertainty about societal choices that determine greenhouse gas emissions.

We used data from seven different climate models to capture a range of potential future climates in Canada. We obtained high-resolution outputs for the seven different climate models from the Canadian Centre for Climate Services, based on downscaling work undertaken by the Pacific Climate Impacts Consortium (PCIC 2019).[1] For each climate model, we considered two emissions scenarios. Our low-emissions scenario corresponds with the Representative Concentration Pathway (RCP) 4.5 scenario described in the Intergovernmental Panel on Climate Change's (IPCC) fifth assessment report. This scenario generally reflects greenhouse gas emissions reduction policies announced globally in 2020, which would result in 2.5 degrees Celsius of global warming, and 4 C of warming in Canada by the end of the century. Our high-emissions scenario corresponds with the IPCC's RCP 8.5 scenario and reflects a future where current rates of growth of global greenhouse gas emissions continue. This scenario projects an average temperature change of 7.4 C in Canada by the end of the century.

As there are currently no comprehensive projections of permafrost thaw in Canada, we worked with permafrost researchers to create potential permafrost thaw risk projections from now to the year 2100 for a ten-by-ten kilometre grid across the North (O'Neill et al. 2020; Obu et al. 2018). We then calculated a risk score for each grid cell using daily climate model projections of future temperature change and estimates of current ground temperature (Smith and Riseborough 2002). We used these risk scores to estimate the level of repairs and replacements needed for infrastructure located within each grid cell.

Finally, we used the Infrastructure Planning Support System (IPSS) to estimate the repair and replacement costs of permafrost thaw and

[1] The seven global climate models used were: CCSM4, GFDL-CM3, GFDL-ESM2M, HadGEM2-AO, HadGEM2-ES, MIROC-ESM-CHEM, and MRI-CG-CM3. The Canadian Centre for Climate Services and Pacific Climate Impacts Consortium provide downscaled daily projections of temperature and precipitation from 2041 to 2100 on a roughly ten-kilometre-by-ten-kilometre grid for all of Canada (PCIC 2019).

temperature rise on airports, roads, and buildings (Melvin et al. 2016; Ness et al. 2021; Resilient Analytics 2021). The IPSS model overlayed the permafrost risk data and temperature data (in the case of winter roads) with information about building, road, and airport locations and characteristics (DMTI Lightbox 2020; Microsoft 2019). The model then analyzed the damage that exposures to future climate hazards could cause to specific infrastructure and quantified the cost of repairing that damage.[2]

All cost estimates in our results section represent the change in cost from the historical average of costs between 1986 and 2005. All costs are in 2019 Canadian dollars and are undiscounted.

As building supplies and labour often cost far more in Northern Canada than in southern Canada, our cost estimates reflect this disparity. For instance, housing construction in Inuit Nunangat costs, on average, $250 to $530 per square foot, compared to $120 to $195 elsewhere in Canada (ITK 2019). To estimate the cost of infrastructure repair and replacement in the Northern context, we developed a cost index to scale the cost of construction and materials at various locations using data on the costs of food in different areas across the North (Nutrition North 2020; Statistics Canada 2016). The Industrial Economics Inc. technical report provides additional details on the methodology.

Our analysis for winter roads differs slightly from the analyses of airports, roads, and buildings because winter roads are primarily impacted by overall warming, not permafrost thaw. We modelled the effects of climate change on future winter road viability by using projections of daily air temperature to estimate the length of time a winter road would be viable. To capture uncertainty due to water salinity and movement, snow cover, and wind, we used two different thresholds to estimate winter road viability. Under the low-sensitivity threshold, a road was not viable if there were no months during a year that consistently had a four-month moving average temperature below -5 degrees Celsius. The high-sensitivity threshold deemed a road 'non-viable' if the temperature of a two-week moving average exceeded -5C (Boehlert et al. 2021).

In addition to modelling impacts associated with two different global greenhouse gas emissions scenarios, we also examined the benefits and potential cost savings of implementing adaptation actions to protect infrastructure from permafrost thaw and other climate change impacts (see Box C). The specific adaptations we modelled varied by infrastructure type and their application is described in more detail in the discussion of results. The adaptations we modelled are not the only viable options, of course. These particular adaptations were selected because they represent commonly used practices across the circumpolar North and can be modelled with confidence.

[2] The IPSS model was developed at the University of Colorado and has been used for similar analysis by the State of Alaska and in the Institute's report, *Under Water*.

BOX C

Arctic Bay, Nunavut. Photo: Dylan Clark.

Infrastructure adaptations for thawing permafrost

There are a number of engineered adaptation measures that can help alleviate the impacts of permafrost thaw and protect infrastructure that is constructed on it or in it—at least temporarily.

In some locations, cooling the ground—called passive cooling—is an effective approach to prevent or slow permafrost thaw. We modelled two approaches to passive cooling: embankment cooling for roads and runways and thermosyphons for buildings.

Embankment cooling practices are used in the North to prevent permafrost from thawing underneath roads and runways. Air cooled embankment systems use highly porous materials such as boulders or cobble to construct the road embankments. This approach helps keep the sides of roads and runways cooler through natural air flow during winter months (Doré et al. 2016). Removing snow from the side of the roads or runways during winter months further prevents thawing by allowing the air to continue to flow through the embankment.

Thermosyphons are refrigeration devices that draw heat from the ground and release it into the air. Sealed pipes are installed vertically or in an L-shaped configuration, with one end below ground and the other above ground. When the ground is warmer than the air, the liquid at the bottom of the tube turns into a gas and rises—moving heat from the ground into the air (Standards Council of Canada 2020). The Northern Infrastructure Standardization Initiative (NISI) includes thermosyphons as an important adaptation tool for buildings in permafrost regions.

When preventing permafrost thaw is not practical or is cost prohibitive due to the speed of climate warming or because of the amount of infrastructure exposed, infrastructure can be stabilized by changing the approach to constructing foundations. We modelled one of these techniques, known as base layer reinforcement, for roads and runways where moderate ground shifting and slumping were projected. Base layer reinforcement tends to be less expensive than thermosyphons.

Base layer reinforcement is a method that involves building embankments with multiple layers of permeable fabrics that help to reinforce, protect, and drain soil, helping infrastructure resist the structural consequences of permafrost degradation (Doré et al. 2016).

While these adaptation measures have been successful at preserving permafrost and stabilizing infrastructure in Northern regions, their installation and operation costs are often extremely high because they require virtually complete reconstruction of the infrastructure they are designed to protect. Currently, they are generally used only for existing infrastructure that is extremely vulnerable, or in new construction of larger commercial and public buildings, highways, and runways. There are no adaptation measures available for Northern infrastructure to significantly reduce the risk of permafrost thaw while maintaining the existing infrastructure in place.

Double Mer, Nunatsiavut. Photo credit: Bird's Eye Inc.

Our modelling provides a useful high-level estimate of the potential impacts and costs of permafrost thaw on infrastructure. However, to complete our analysis, we needed to make a number of simplifying assumptions.

Notably, there are large gaps in information about the extent and characteristics of permafrost as well as the costs of repairing infrastructure in Northern Canada. As a result, our permafrost thaw damage index estimated permafrost characteristics based on other climate information, and our cost calculations used data from previous studies in Alaska. Therefore, our analysis provides useful projections of national and regional level costs but does not provide detailed estimates of impacts and costs for each municipality and community that is affected.

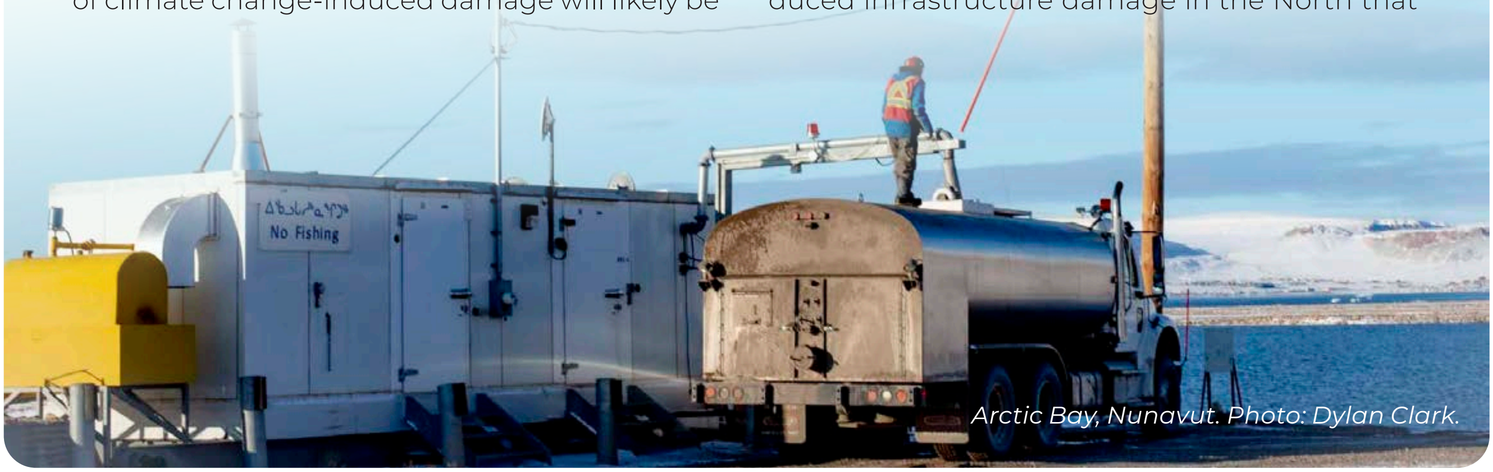
Furthermore, our costing estimates are based on impacts to the existing stock of infrastructure in Northern Canada, and do not attempt to predict where infrastructure will be built in the years to come—including the significant amount of infrastructure that is needed to close the Northern infrastructure gap. This omission is a common assumption of many studies that look at the economic impacts of climate change, but because population growth is presently higher in the North than in any other region of Canada, our results are almost certainly conservative. Therefore, the costs of climate change-induced damage will likely be substantially more than our estimates, as will the benefits of adaptation.

Additional information about our modelling methods is available in the accompanying technical report (Boehlert et al. 2021).

Lived experiences and community impacts

There are many climate-related infrastructure impacts that are impossible to model or assign a dollar value to—the impacts to people's well-being and to the social fabric of communities, damage to cultures, threats to food security, and loss of treasured ecosystems and landscapes. To better convey these impacts, we collaborated with Firelight Group, an Indigenous-owned consulting firm that has worked with many communities across the North, to examine how permafrost thaw and other climate-related impacts to infrastructure are affecting life for Indigenous Peoples. This work is based on interviews conducted in six different communities across the North from September 2021 to October 2021 (Firelight 2022).

We used the findings of Firelight's research to better understand the potential social, cultural, and economic impacts of the climate change-induced infrastructure damage in the North that



Arctic Bay, Nunavut. Photo: Dylan Clark.

we modelled. We highlighted Firelight's findings throughout this report, using quotes from interviews that convey important perspectives from people who are living through climate change in the North. Firelight's analysis can be found in their companion report (Firelight 2022).

The Firelight findings in this report and the companion report are not intended to speak to the experiences of all Indigenous Peoples across the North. Because of the diversity in lived experiences and cultures across the North and the small sample size, the participants' experiences do not reflect all the ways that climate change will affect Northern infrastructure, nor do they capture all the ways that infrastructure damage may impact well-being and ways of life.

Finally, while this report focusses on the impacts of climate change on infrastructure, it is important to note that there are many other ways that climate change is affecting people across Northern Canada. Despite these limitations, Firelight's research still helps to demonstrate the breadth of losses and the indirect effects of permafrost thaw beyond just the costs of repairing and replacing infrastructure.

Our results are presented in four sections: one for each of the three types of infrastructure we assessed—airports, roads, and homes and buildings—followed by a discussion of what we heard from Northerners through Firelight's findings and through our engagement with decision makers, rights holders, and stakeholders.

"Often, I think of the changes I have seen and it [climate change] really alters everything, not only the environment, it changes the landscape, it changes the habitat.... changes everything—caribou, geese, and we also have a species of trees that we haven't seen before.... I think there's all of the changing landscape—it's changing everything."

—Ontario participant (Firelight 2022)

Rigolet, Nunatsiavut. Photo: Bird's Eye Inc.

Pangnirtung, Nunavut. Photo: Dylan Clark.

CLIMATE IMPACTS ON **AIRPORTS**

Airports are essential infrastructure for communities across the North and are relied on for travel, delivery of fresh food, and services like medical care. For the 68 fly-in communities in the North, airports are particularly important. Most of these fly-in communities are in the eastern Arctic (Table 1), while in the western Arctic, most communities are connected by roads. In Nunavut, all communities are fly-in, while in Yukon, all but one community have all-season roads.

Our airport analysis focused on the impacts of permafrost thaw and rising temperatures on runways. In total, we estimated the impacts and costs of climate change on 149 runways across the North. We have also integrated some discussion of climate impacts on other components of air transportation systems, such as safety equipment and weather forecasting.

We analyzed impacts on both paved and gravel runways. Most of the runways in the North, and most of the runways we assessed in this report, are gravel (Table 2). Paved runways are more costly to build than gravel but can accommodate larger aircraft that carry more cargo and people. The few paved runways in Northern Canada are found in the northern regions of British Columbia, Alberta,

Table 2

Northern airport runways analyzed in this report

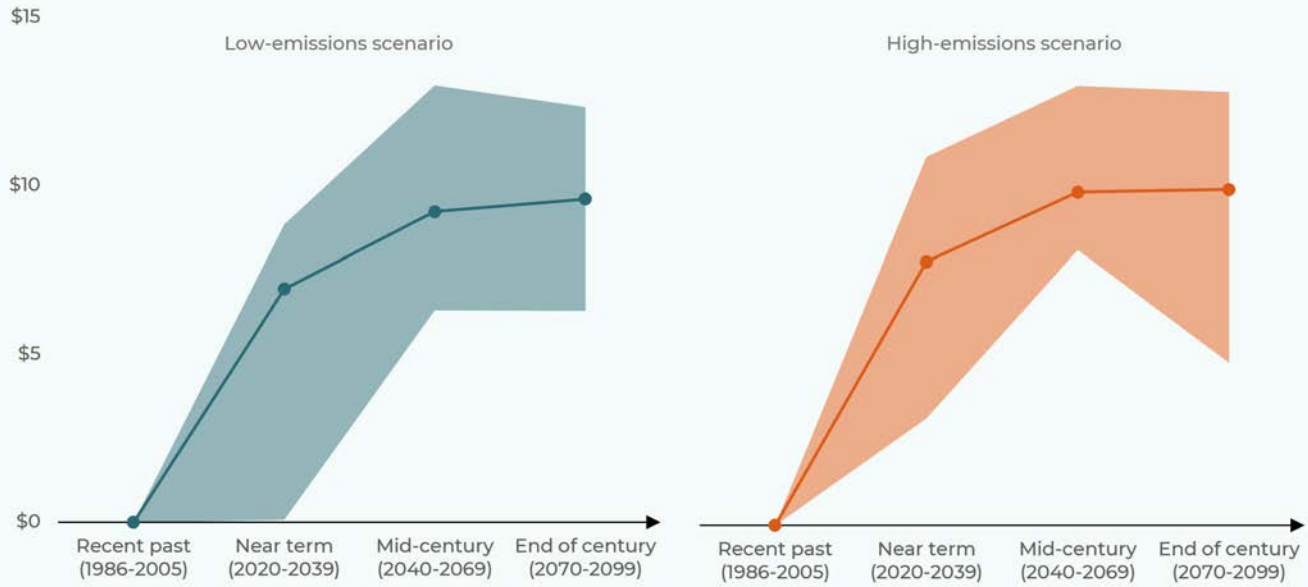
Province or territory	Number of airports*	
	Gravel	Paved
Nunavut	23	2
Northwest Territories	22	6
Yukon	14	2
Nunavik	13	1
Nunatsiavut	5	0
Northern regions of provinces west of Quebec	29	32

*Numbers reflect the airports analyzed in our analysis, not the total number of airports in the North. Private airstrips are not included.

Figure 5

Costs of runway damage are rapidly increasing across the North

Projected annual costs of runway damage in millions of dollars (2019 CAD)



In our figures, each line reflects the median projected values of seven global climate models (GCMs). Shaded areas behind each line capture the range between the maximum GCM value and the minimum GCM value for each scenario. Teal lines and areas represent results under a low-emissions scenario. The orange lines and areas represent a high-emissions scenario.

Saskatchewan, Manitoba, and Ontario, and in the capitals and regional hubs in the territories.

All Northern airports face climate change impacts to runways. Some airports in the North are already experiencing damage from permafrost thaw. Prominent examples include:

- The Government of Northwest Territories is spending $22 million to protect the Inuvik airport from the impacts of climate change and reduce ground settlements from permafrost thaw that have already occurred (Infrastructure Canada 2019).
- The Royal Canadian Air Force is no longer able to regularly land large planes such as the C-130 at some northern Nunavut airports due to runway slumping and degradation.
- The Iqaluit International Airport recently underwent $300 million worth of improvements, including extensive repairs to runways that had cracked and warped due to permafrost thaw (Wallace 2019).

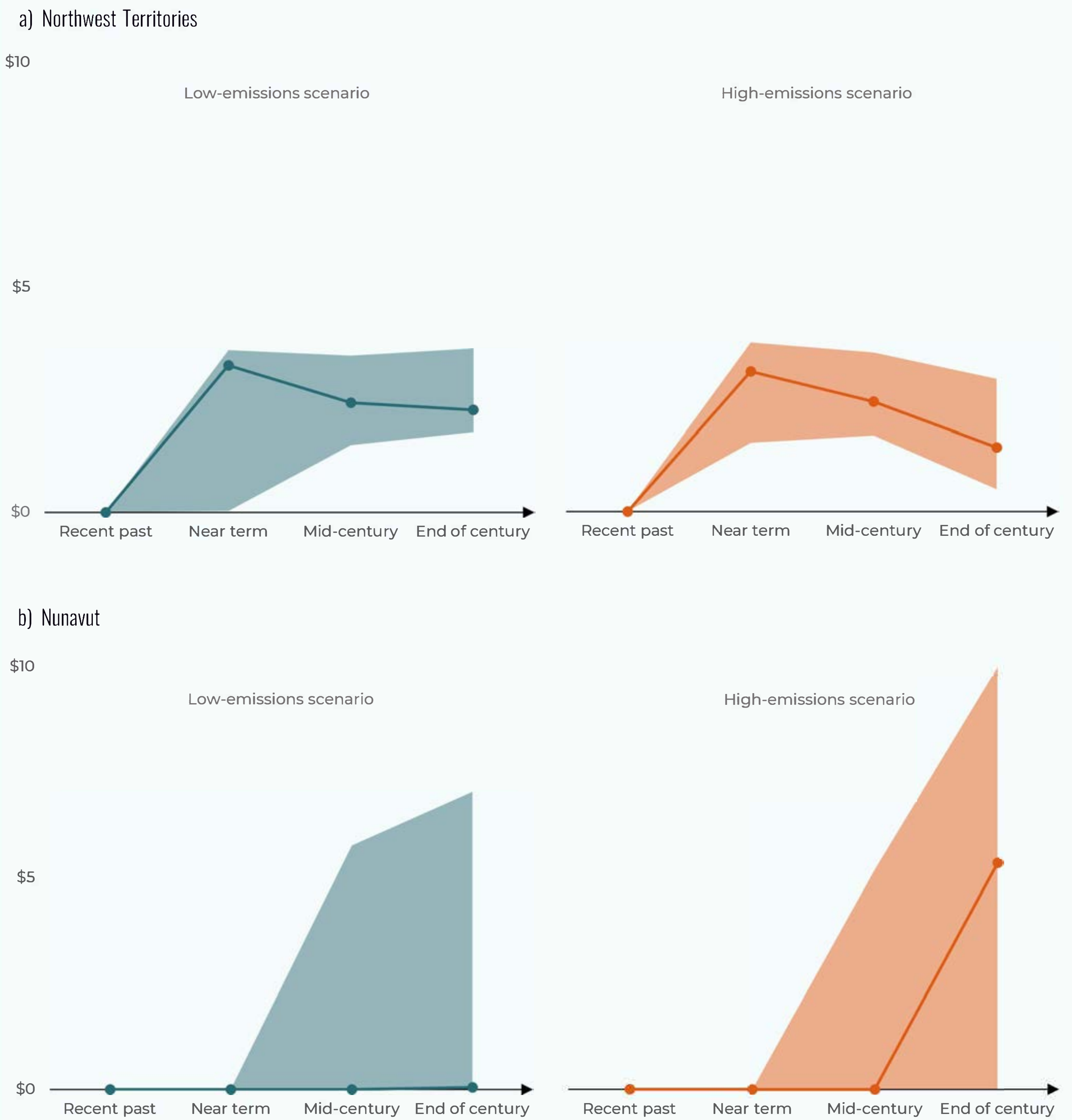
Without adaptation, national costs from permafrost thaw damages to runways are likely to continue to rise for the next 20 to 30 years and then remain high throughout the rest of the century. We project a median cost of $7 million per year in 2040 alone (Figure 5).

In the near term, costs are likely to be highest in Northwest Territories (Figure 6), where permafrost is thawing more quickly and where more airports are on ground that thaws in the summer and refreezes in the winter (there are fewer airports built on permafrost in Yukon). We project that without adaptation, the permafrost damage to runways in Northwest Territories could increase by

Figure 6

Costs of runway damage related to climate change vary across the North

Projected annual costs of runway damage in millions of dollars (2019 CAD)



$3 million per year above the costs in the late 20th century in the near term—approximately 35 per cent of the Northwest Territories' current average annual capital expenditures for air transportation (Statistics Canada 2019).

Under a high-emissions scenario the permafrost will thaw rapidly in Northwest Territories, leading to the near-complete thaw of top layers by the end of the century. Although costs under a high-emissions scenario might be lower than in a low-emissions scenario in some places due to a more rapid loss of permafrost (see Figure 4), our analysis does not include the significant cost of damage from other climate change hazards to runways. These hazards include increased temperature and precipitation, which would be more intense and costly under the high-emissions scenario. We discuss some of these risks in the following section.

Airports in the high Arctic may not experience severe damage until later in the century. Although Nunavut has more airports than any other region, it also has the coldest average temperatures in Canada and the permafrost will take longer to thaw. Our analysis projects that costs in Nunavut will therefore remain low until the end of the century under a low-emissions scenario. Under a

Parry Channel, Nunavut. Photo: Dylan Clark.

> "Here's the runway.... Built by military, of course.... And this entire area... is marshland.... It's been sinking for I don't know how many years due to permafrost [thaw]."
>
> *—Nunavut participant (Firelight 2022)*

high-emissions scenario, Nunavut will only begin to see significant impacts in the latter half of the century. Once Nunavut starts to see those impacts, however, resulting damages could cost an estimated $5 million annually (Figure 6).

There is also a high level of uncertainty around the extent of temperature change later in the century. As a result, there is a wide range of possible impacts. One of the climate models we used results in estimates of cost increases of about $10 million per year for Nunavut, while another results in estimates of negligible impacts and costs.

Northern airports face many climate-related threats beyond permafrost thaw

Beyond permafrost thaw, changes in weather patterns—including to temperature, precipitation, and wind direction—will also affect airport maintenance costs and reliability.

Increases in rain and snow in the North will introduce many new maintenance costs. There may be increased demand for snow removal and the re-gravelling of runway surfaces because of more frequent snow and ice clearing (Government of Nunavut 2014). As the North experiences warmer winters, temperatures will start to hover around zero degrees Celsius rather than well below it, leading to more frequent freeze-thaw cycles causing gravel and paved runways to degrade more quickly (Allard et al. 2012).

Warmer temperatures will also necessitate longer runways to handle the same types of planes currently used in the North (Coffel et al. 2017). Warmer air is less dense, so airplanes need to take off at a higher speed to obtain the same lift as in colder weather. To reach this higher speed, planes need a longer runway. Because runways across the North are already significantly shorter in length than those in the south, they may need to be extended, often at significant cost. Planes could also be forced to reduce the number of passengers or amount of cargo they can carry on hot days.

Climate change is also shifting the dominant wind direction in some Northern regions. Wind makes it more difficult to control aircraft during take-off and can increase weather delays (Zhao and Sushama 2020). Over time, changes in wind direction are expected to make some runways, such as those at Iqaluit's airport, less reliable due to increasing crosswinds. In other Northern regions, icing conditions could become more frequent over the coming decade as the moisture in the atmosphere increases with warming. Airports could thus be required to invest in new equipment to combat the ice, and the use of anti-icing sprays can increase runway maintenance costs and accelerate permafrost thaw.

Climate change could increase the frequency of extreme weather events such as thunderstorms, hail, and even tornados, and Northern aviation equipment is not well prepared for the growing threats posed by these storms (Brown et al. 2020; Chen et al. 2021). Currently, there is no weather radar coverage in the North, and many airports lack critical safety equipment such as lights. More frequent extreme weather, coupled with limited capacity for forecasting, could result in more unplanned airport outages, inhibiting the movement of people and goods.

Adaptations can reduce costs and ensure that communities have reliable airports

Our analysis considered adaptations such as base layer reinforcement and embankment cooling, which are widely used for Northern airports. Other important adaptations to consider, however, that were not part of our analysis, include planned failure, relocating airports, building gravel instead of paved runways, and improving weather forecasting, radar, navigation systems, and safety equipment. In practice, all the adaptation approaches mentioned below will need to be site-specific.

Base layer reinforcement and embankment cooling can play a role in reducing the impacts and costs of permafrost thaw on airports (see Box C), although cost savings from these adaptation measures vary across the North. In Nunavik, where permafrost thaw is likely to occur earlier, incremental adaptations could reduce annual net costs by 74 to 88 per cent on average, depending on the global greenhouse gas emissions trajectory. We found similar levels of cost savings in Northwest Territories and Yukon (Table 3). In Nunavut, where damages will occur later in the century, base layer reinforcement and embankment cooling could reduce damage costs by more than half by the end of the century in a high-emissions scenario. The cost savings are lower, especially in a low-emissions scenario, because some savings will be realized after 2100. This parallels findings from some site-specific studies that show positive return on investments for incremental adaptation measures (Brooks et al. 2017).

Table 3

Airports across the North and potential cost savings from adaptation

Region	Number of airports	Adaptation cost savings per year (millions $)	
		Low emissions	High emissions
Yukon	16	1.48	0.93
NWT	28	2.43	2.06
Nunavut	25	0.01	1.95
Nunavik	14	1.17	1.65
Nunatsiavut	5	0 (negligible permafrost)	0 (negligible permafrost)
Northern regions of provinces west of Quebec	61	1.74	1.17

Several adaptation measures outside the scope of our analysis, including planned failure, relocating airports, and building gravel instead of paved runways, can also be useful tools. Case studies in Nunavik and northern Saskatchewan indicate that these options also have potential to reduce direct and indirect costs (George 2006; Uzarowski et al. 2018). In practice, adaptation approaches will need to be site-specific and will likely use a variety of incremental and transformative adaptations as well as other practices.

There are also adaptations that can fix current deficiencies and safety issues at Northern airports. For example, improvements to weather forecasting, radar, navigation systems, and safety equipment can all help airports better withstand future climate-related hazards (Bouchard 2020). However, current airport funding structures are a major obstacle to implementing such adaptation measures (Box D).

Adaptation actions can reduce the risk of airport service interruptions, bolster regional security, and ensure that the fundamental needs of Northern communities are being met (Dorough et al. 2021). The costs and savings we modelled only reflect direct damages, and do not factor in the value of other social and economic benefits from infrastructure, including access to critical medical care, food security, economic activity, and the transport of essential equipment.

Whale Cove, Nunavut. Photo: Dylan Clark.

Akuvalik Airport, Nunavik.

Northern governments face barriers in securing airport funding

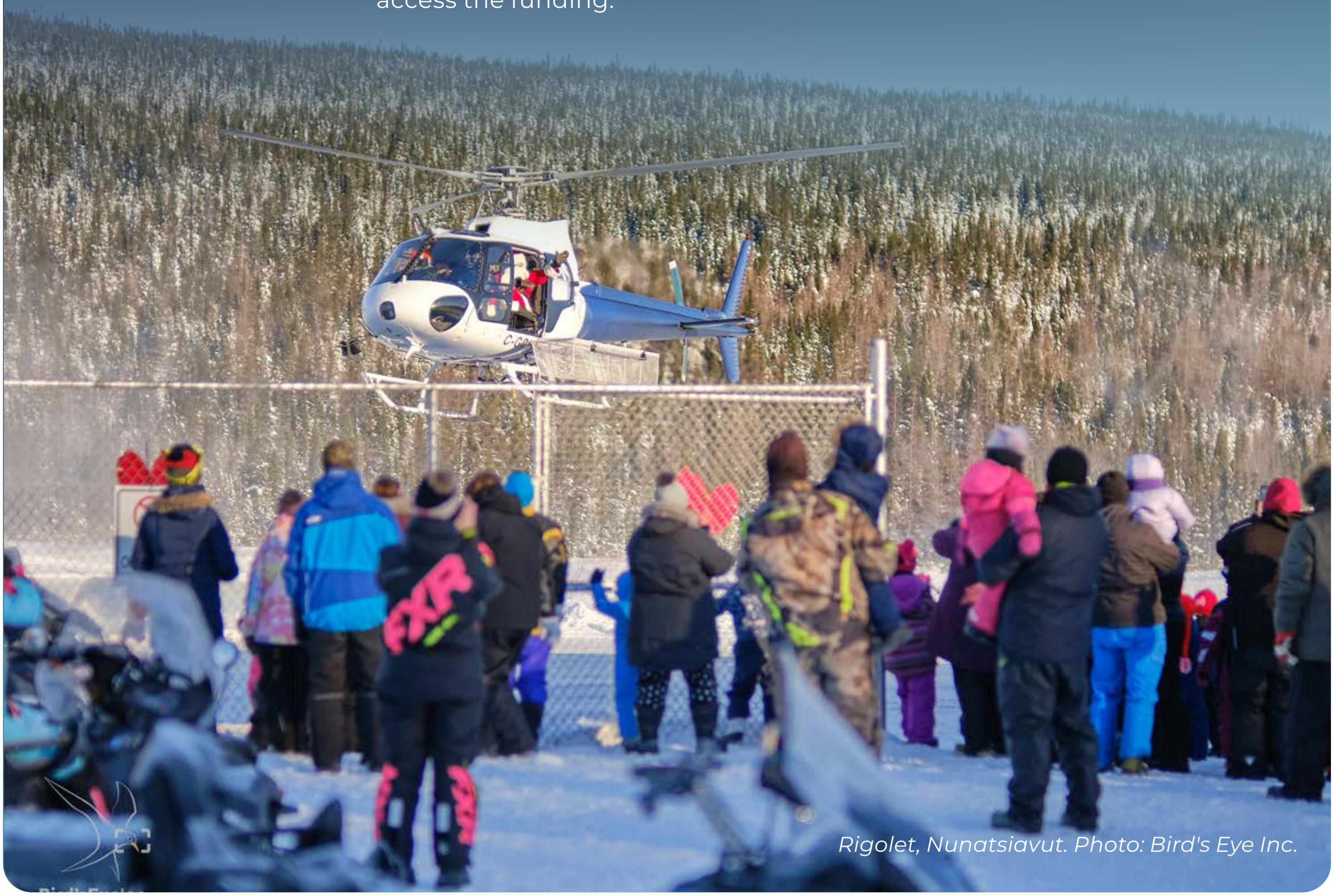
Northern governments struggle to maintain airports and prepare runways and terminals for climate-related hazards, and the challenge is due, at least in part, to deficiencies in funding structures.

Over the past 30 years, the federal government has transferred ownership of most airports to provincial and territorial governments. In 1995, most public airports in the North were owned and managed by the federal government. As of 2022, only two Northern airports are still federally owned, and the rest are operated by provincial and territorial governments (Transport Canada 2022a).

Transport Canada is still responsible for promoting safe and secure air transportation, even though the federal government no longer owns and operates most airports across the North (Office of the Auditor General of Canada 2017). In 2017, the Office of the Auditor General assessed the Government of Canada's delivery and leadership over Northern air transportation. The audit found that despite knowing about critical infrastructure needs, Transport Canada "had not taken a leadership role in addressing these needs by leading efforts and working collaboratively with its provincial, territorial, and industry partners to enhance the safety and improve the accessibility and efficiency of remote northern airports."

As an example of the issue raised by the audit, the Airports Capital Assistance Program run by Transport Canada—a primary funding source for small airport capital costs—has been perennially underfunded. Since 1995, Canada has contributed $1.1 billion to eligible airports, an average of about $30 million per year across all small airports in Canada (most of which are in southern Canada). However, the Auditor General notes that over $100 million is needed in a three-year period in the North alone (Transport Canada 2021; Office of the Auditor General of Canada 2017).

Even where funding programs exist, they are not accessible to many of the territorial and municipal governments that own and operate Northern airports. Only airports that are certified by Transport Canada—indicating that they meet certain safety thresholds—or airports that are close to being granted this certification are eligible to apply for funding through the federal program. We found that 30 per cent of airports across the North have not yet been certified. This funding requirement creates a catch-22: Northern governments need money to make safety improvements, but because their airports do not meet safety requirements, they cannot access the funding.



Rigolet, Nunatsiavut. Photo: Bird's Eye Inc.

Dempster Highway at Tombstone Territorial Park, Yukon.

5

"The pavement, especially the new pavement, it gets hot and melts what's underneath it, and then it just collapses. There's a few roads in town where you could tell a section of the road has collapsed.... You have that all over town."

—Nunavut participant (Firelight 2022)

CLIMATE IMPACTS ON **PERMANENT ROADS** AND **WINTER ROADS**

All-season and winter roads connect communities across the North to medical care, food, and fuel. Roads are also essential for servicing one of the North's largest industries: mining (Box E). Across the North, mining companies maintain many winter roads to move supplies and product. In some regions, residents and community members also use these roads.

Roads play a wide variety of roles across the North. In Yukon, all-season roads connect every community in the territory except Old Crow, and the majority are paved (Table 4). In the Northwest Territories, paved roads are less common, and fewer communities are connected to all-season road networks. In the eastern Arctic—Nunavut, Nunavik, and Nunatsiavut—roads are almost entirely located within municipal limits, with no all-season roads connecting communities.

In our analysis of winter roads, we modelled the impacts and costs of damage induced by permafrost thaw on paved and gravel roads across the North and examined the impacts of warming on winter road viability. We included both publicly maintained winter roads and some winter roads that are maintained by mining companies.

Without adaptation, major road damage and disruption will persist for decades

Permafrost thaw can cause roads to degrade, crack, or even collapse, making them unusable in some cases.

BOX E

Climate change is threatening mine infrastructure across the North

"The government[s] that build these roads want to make sure that they have a return once… their project is completed. And I know up here in the North we do have a lot of potential for mining.… We do have the mine just 50 kilometres north of Whatì, and that's been there for quite a while now. I mean, they did need the road to take their product out, and I understand it's a junior company that requires some investors.… But the government looks at these and that way… you know, it's worth building a road."

—Northwest Territories participant (Firelight 2022)

Mining is prevalent across Northern Canada and contributes significantly to regional economies. In Yukon, the mining sector makes up almost 10 per cent of the territory's gross domestic product (GDP) and contributes about 1,500 jobs (Yukon Bureau of Statistics 2020; NRCan n.d.).

Mining operations in Nunavut—which are some of the largest in the North and import more labour from southern Canada than other Northern territories—generate about 25 per cent of the territory's GDP, while mining in Northwest Territories generates about 30 per cent of the territory's GDP (Statistics Canada 2021a).

Roads, airports, ports, and electricity systems are all important infrastructure for mining operations. Although Northern mine development has historically prompted governments to expand infrastructure networks, poor infrastructure continues to limit the viability of mining in many places.

Climate change is shifting how and where resources can be mined safely across Northern Canada. Permafrost thaw is not only affecting the transportation networks used to move equipment and ore, but it also introduces new risks of large-scale environmental contamination in cases where the infrastructure to contain mine waste, such as tailings ponds, is not built appropriately (Golder 2021). Changes in winter road seasons are limiting when mines can operate at full capacity and which routes are used for exports. Climate-related impacts to electricity systems and freshwater resources are also prompting closer analysis of the environmental and social effects of mining.

Table 4

Northern permanent roads and winter roads analyzed in this report

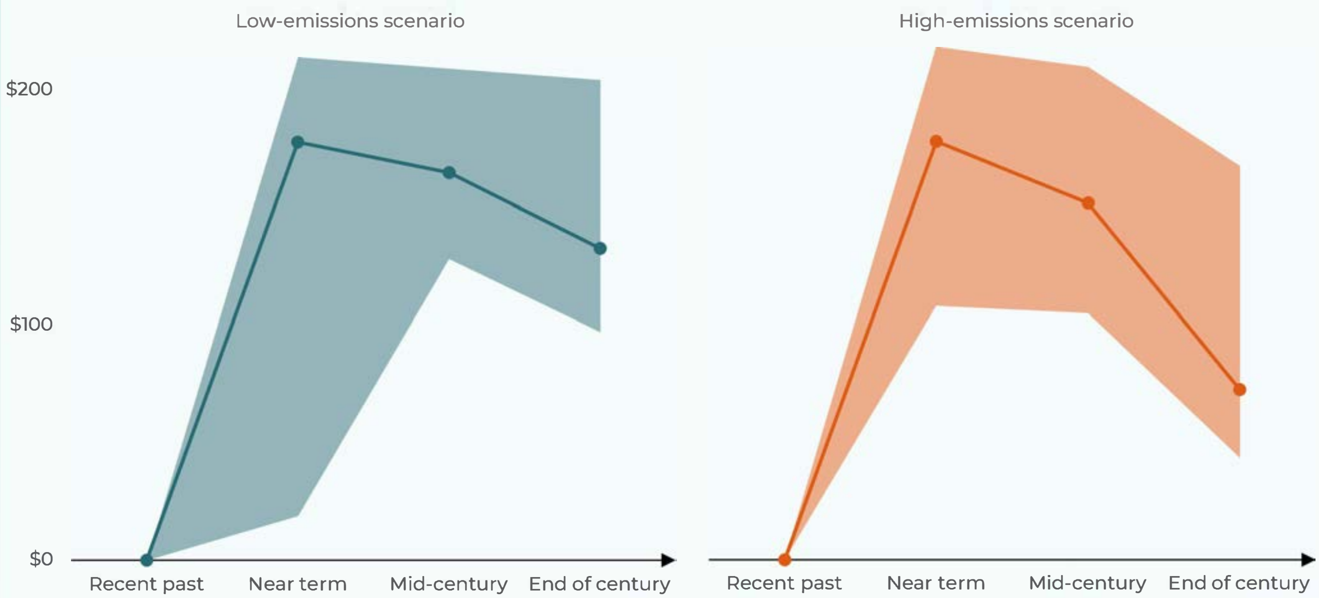
Region	Kilometres of permanent roads analyzed (paved and gravel)	Kilometres of winter roads analyzed
Yukon	8,400	<10
Northwest Territories	3,800	2,000
Nunavut	500	100
Nunavik	200	0
Nunatsiavut	25	0

Arviat, Nunavut. Photo: Dylan Clark.

Figure 7

Costs of Northern road repair and replacement remain high until the end of the century

Projected annual costs of road damage in millions of dollars (2019 CAD)



Across Canada, the rapid temperature increases projected in the high-emissions scenario will cause costs to rise quickly, with a more exaggerated peak, before costs decline toward the end of the century (Figure 7). This is because in most of the North (Yukon, southern Northwest Territories, Nunavik, and the northern regions of provinces), faster warming caused by higher emissions will cause the upper layer of permafrost to thaw almost completely over the next 80 years. Without adaptation, these rapid spikes in damage and costs will be challenging to manage—in terms of both capital costs and necessary repairs to keep roads open.

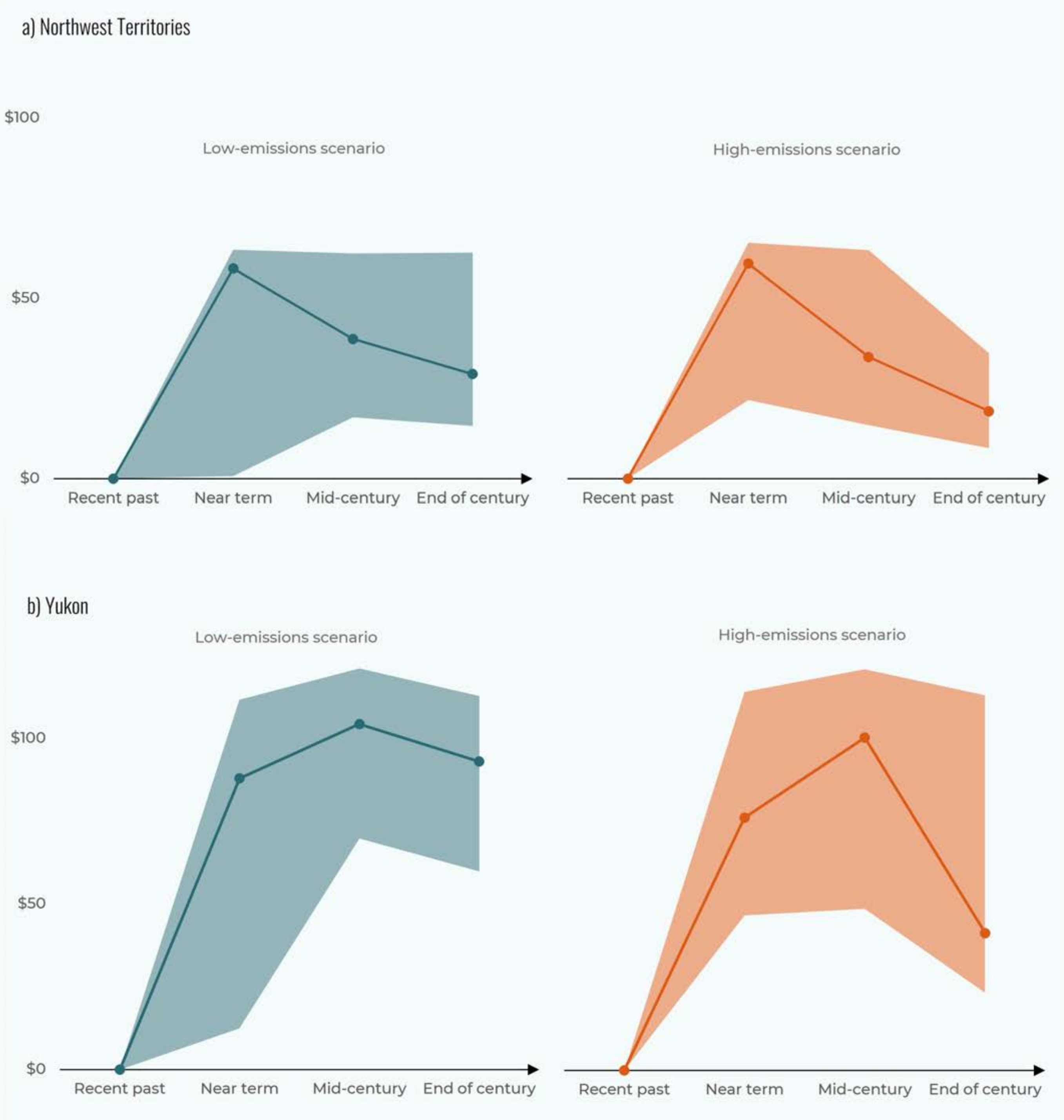
Our analysis suggests that damage to gravel roads will cost less per kilometre than those for paved roads; gravel roads are usually easier to repair or regrade when damaged by permafrost thaw, while paved roads generally need to be replaced or retired more quickly.

Of all the infrastructure types we modelled, damage to all-season roads and winter roads created the highest costs for Yukon and Northwest Territories (Figure 8). In Yukon, we project that, without adaptation, the average cost of permafrost damage to both paved and gravel roads will be between $73 million and $85 million per year for the next two decades. To put these

Figure 8

Costs of road damage could exceed $50 million annually in Northwest Territories and $70 million in Yukon

Projected annual costs of road damage in millions of dollars (2019 CAD)



figures in context, the projected costs of road damages for Yukon represent 75 to 90 per cent of current total annual spending on roads (Statistics Canada 2019). By the 2060s, the costs of permafrost damage to roads could surpass the current budget by 26 per cent, even in a low-emissions scenario. In Northwest Territories, we found that, without adaptation, the projected cost of damages to paved and gravel roads is approximately $55 million per year for the next few decades—about 15 per cent of 2020 infrastructure capital expenditures for the Government of Northwest Territories (Government of Northwest Territories 2020).

We expect costs to accelerate at higher latitudes as temperatures continue to increase. Although there are fewer roads across Northwest Territories and Nunavut, damage will continue until later in the century, particularly under a low-emissions scenario in which permafrost would thaw more slowly.

Adaptations for paved and gravel roads can save money and reduce the risk of service disruptions

Our modelling shows that base layer reinforcement and embankment cooling can reduce the costs of road repair and replacement in some conditions by delaying permafrost thaw.

In a low-emissions scenario, if base layer reinforcement and embankment cooling are used on paved roads, they could reduce costs by 38 to 42 per cent on average in Yukon and Northwest Territories, depending on the location. For gravel roads, these adaptations could reduce net costs by 27 per cent in Yukon.

However, in a high-emissions scenario, there would be significant adaptation investments required by mid-century, which could reduce damage costs by 23 per cent but do not provide a positive return on investments.

In short, base layer reinforcement and embankment cooling have practical limitations. These adaptations can delay permafrost thaw, but in a high-emissions scenario, temperatures in many areas will rise so high that these adaptations cannot prevent thawing and damage.

Our model also indicates that in a high-emissions scenario, base layer reinforcement and embankment cooling could actually increase the annual costs of maintaining gravel roads by about 25 per cent. In these cases, practices like pre-thawing permafrost and rebuilding the road may be more cost effective while better protecting services (Connor et al. 2020).

There are financial limits to these types of adaptations for roads on permafrost. Embankment cooling and base layer reinforcement are expensive to implement and are generally only deployed by highway departments at the most critical locations. In our analysis, for example, the adaptation scenario assumes that air-cooled embankments are only applied to the most critical 11 per cent of primary and secondary gravel roads situated on permafrost. Broader application would result in greater costs than benefits.

Despite their limitations, incremental adaptation measures such as base layer reinforcement and embankment cooling could still be worth implementing on Northern roads, as they can prevent social and economic disruptions from road damage in the short term. However, these methods would have to be considered alongside transformative adaptation measures such as excavating permafrost and phasing out and relocating roads, as these adaptations may be better long-term investments. Incremental adaptations are more effective in a low-emissions scenario, while more transformative adaptations such as pre-thawing permafrost (which involves intentionally thawing the permafrost prior to building a section of road, a runway, or a building) may prove to be better long-term investments if a high-emissions scenario plays out.

Winter roads are becoming less viable across Northern Canada, and adaptation opportunities are limited

When lakes and rivers in the North freeze over for the winter, the ice is often thick enough to allow vehicles to drive over it for a few months of the year. These winter roads connect communities that are reachable only by plane or boat for the remainder of the year. But winter roads require consistent below-freezing temperatures for the ice to remain safe for vehicles, and climate change threatens to make winter road seasons shorter or, in some places, entirely unviable.

When winter roads are closed, communities that depend on them risk running out of critical supplies such as food and fuel and losing access to essential services (Hori et al. 2018). People who live in communities connected by winter roads often plan travel around the winter road season to stock up on many months' worth of food, supplies, and household essentials (Firelight 2022; Hori et al. 2018). If winter roads become unusable, communities will be forced to rely on air and sea transportation, or to build very expensive all-season roads, all of which will leave individuals and governments with much higher costs for transportation, food, fuel, and other goods (CBC 2011; Maracle et al. 2018; Brockman and Beers 2018).

Across the North, most winter roads could become unviable by mid-century. In the Northwest Territories—where a quarter of Canada's Northern winter roads are located—more than half of winter roads could become unusable by 2050 and nearly all could be unusable by 2080 (Figure 9). We found similar levels of winter road loss in the Northern regions of Ontario and Manitoba. Most winter roads are in the Northwest Territories, Northern Ontario, and Manitoba, with a small number in Yukon and Nunavut.

To illustrate the economic implications of winter roads becoming inoperable, we estimated the costs of replacing winter roads by building all-season roads. We found that over the next 20 years it could cost at least $2 billion for Northwest Territories to build permanent roads—an unprecedented level of infrastructure spending in that territory. Moreover, in many locations, building all-season roads is not physically possible, so even if funds can be found they are not a practical replacement for the historic winter road network.

Some adaptation measures can extend the viability of winter roads, such as using weather monitoring and traffic management (Barrette and Lawrence Charlebois 2018), spraying the ice surface to increase thickness more rapidly, and laying booms across rivers to aid ice formation (Barrette et al. 2018).

Ultimately, however, even in a low-emissions scenario, and no matter what adaptation actions are taken to prolong road life, most winter roads will become unviable everywhere except the high

“Construction is all pretty well almost complete [on the Tlicho All Season Road], and I’m hearing that it might be opening.... So, if it does happen... [the community] really would be happy that they don’t have to pay too much of a price on the food and whatnot.”

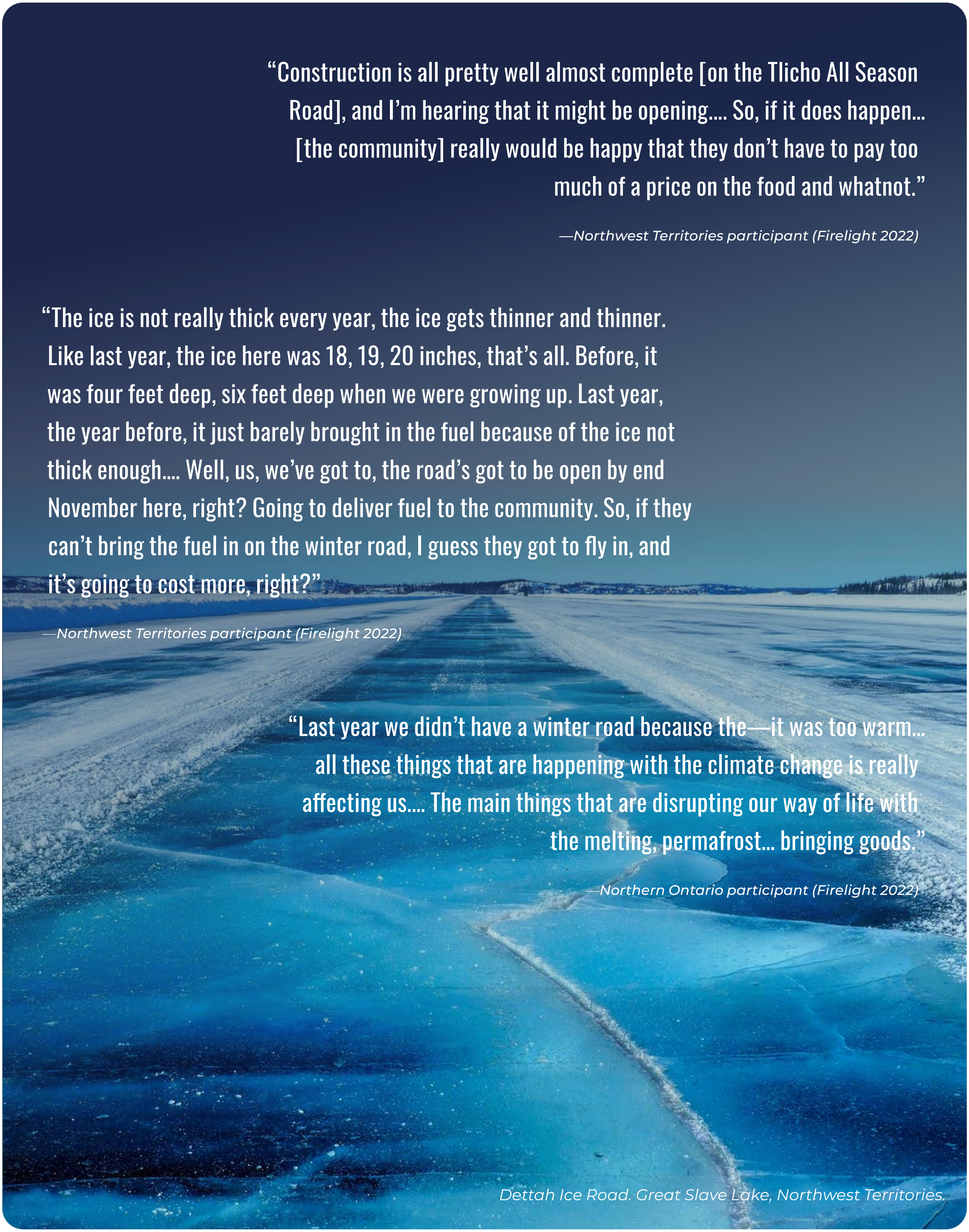
—Northwest Territories participant (Firelight 2022)

“The ice is not really thick every year, the ice gets thinner and thinner. Like last year, the ice here was 18, 19, 20 inches, that’s all. Before, it was four feet deep, six feet deep when we were growing up. Last year, the year before, it just barely brought in the fuel because of the ice not thick enough.... Well, us, we’ve got to, the road’s got to be open by end November here, right? Going to deliver fuel to the community. So, if they can’t bring the fuel in on the winter road, I guess they got to fly in, and it’s going to cost more, right?”

—Northwest Territories participant (Firelight 2022)

“Last year we didn’t have a winter road because the—it was too warm... all these things that are happening with the climate change is really affecting us.... The main things that are disrupting our way of life with the melting, permafrost... bringing goods.”

—Northern Ontario participant (Firelight 2022)

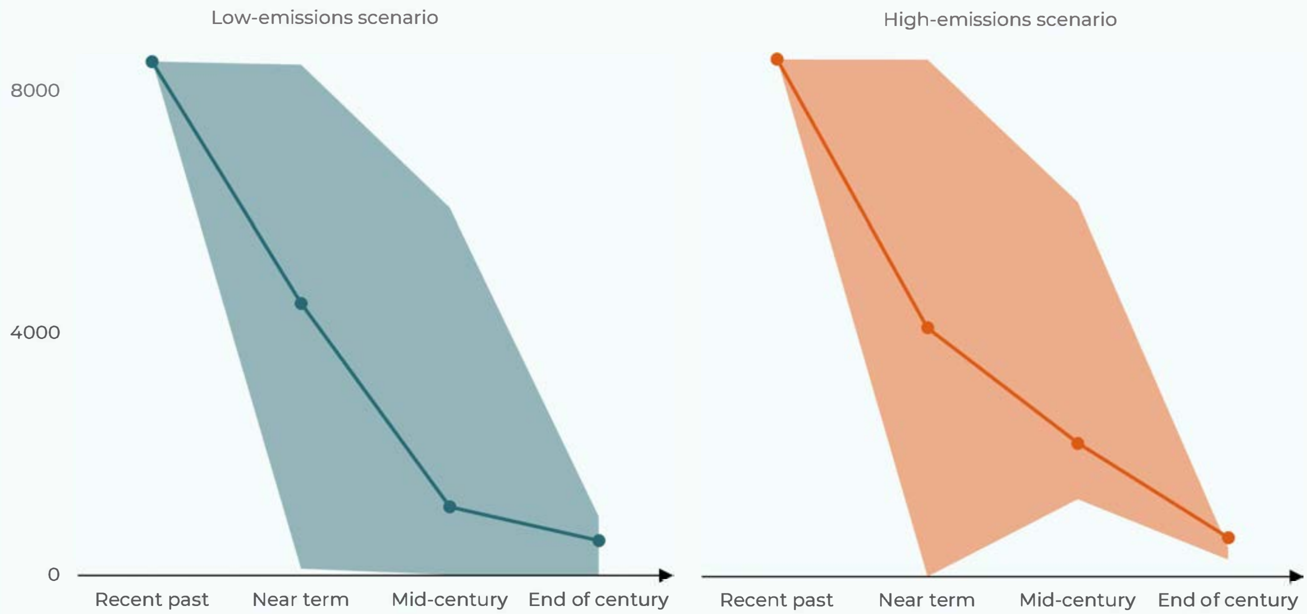


Dettah Ice Road. Great Slave Lake, Northwest Territories.

Figure 9

More than half of winter roads could become unviable in the next 30 years

Projected annual length of winter roads retired (in kilometres)



Arctic by mid-century. Adaptations for winter roads must therefore move beyond incremental adaptation solutions to rethinking the design and development of transportation infrastructures. Communities and governments will need new ways of transporting fuel, food, and other supplies, and some supply chains may need to incorporate more locally produced products or reduce demand on difficult-to-transport products such as fossil fuels. Climate mitigation measures like replacing diesel generators with clean microgrids and electrifying Northern transportation could thus also help to meet Northern adaptation goals.

Arviat, Nunavut. Photo: Dylan Clark.

Yellowknife, Northwest Territories.

6

CLIMATE IMPACTS ON **BUILDINGS**

Permafrost thaw can have catastrophic impacts on buildings. Thawing permafrost underneath a building or home can cause foundations to crack, can lead to failure of the internal building structure, and can damage pipes and gas lines. And once permafrost thaw begins to affect a building's structural integrity, repairing and maintaining the structure can become prohibitively expensive. These damages could be extremely costly for governments as they own many homes and buildings in the North. Business owners and individuals who own their homes will also have to pay for more frequent and extensive repairs, which may not be covered by insurance.

We analyzed the impact of permafrost thaw on the repair and replacement cost of more than 200,000 commercial and residential buildings across Northern Canada. Of these buildings, about 90,000—45 per cent—are currently in permafrost zones. These buildings are mostly located in the Northwest Territories, Nunavut, and Nunavik. Our analysis did not include northern regions of provinces (except Nunavik and Nunatsiavut), as they have relatively few or no buildings on permafrost. Costs were estimated based on a range of repair and replacement decisions for each scenario and do not include any other drivers of building wear and degradation (see Table 5).

Permafrost thaw impacts on buildings will vary throughout the North and will shift northward throughout the century as temperatures rise

Without adaptation, total costs of damage to buildings across the North could reach $30 to $38 million per year by mid-century and $38 to $76 million per year by end of century. Our analysis shows

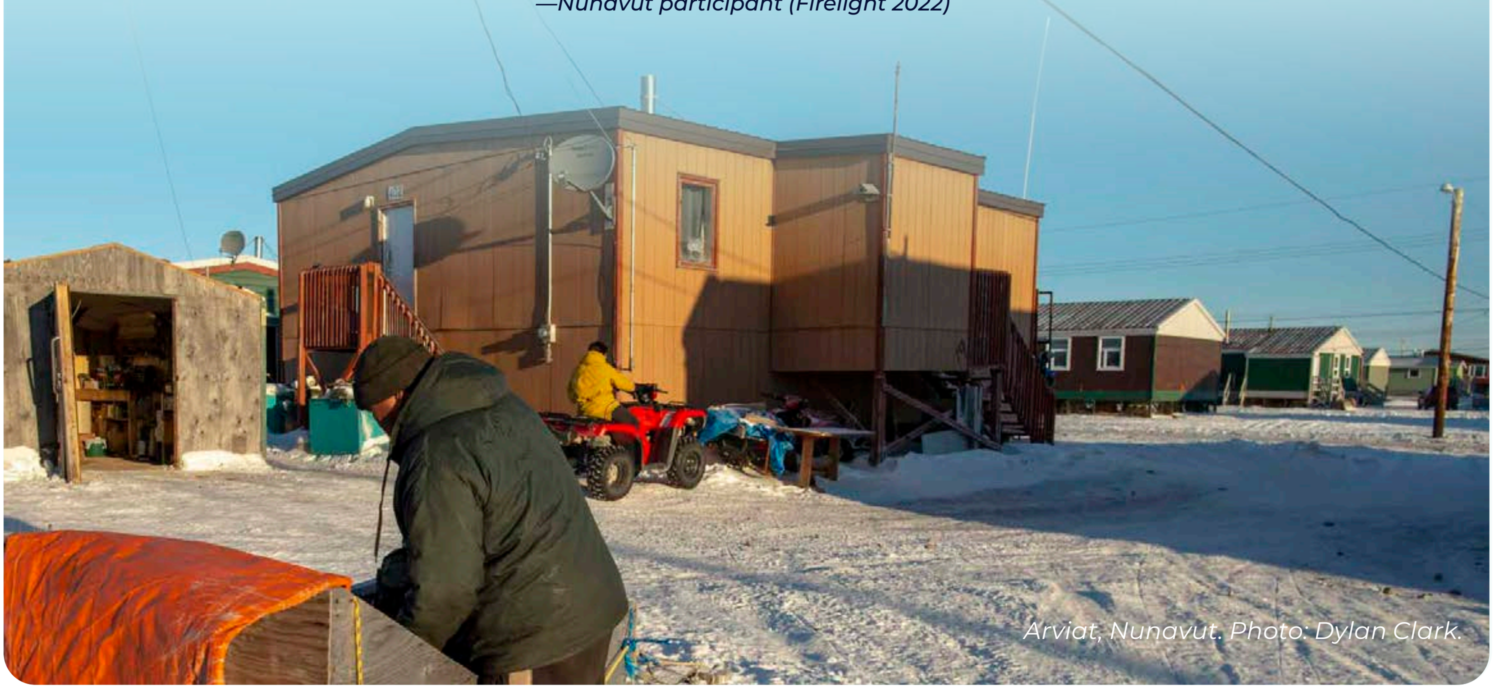
Table 5

Building exposure to permafrost thaw across Northern Canada

Emissions scenario	Building manager response	2050s average buildings per category	2080s average buildings per category
Low emissions scenario	Minimal repairs	94%	93%
	Foundation repairs	6%	7%
	Rebuild or relocate	0	0
High emissions scenario	Minimal repairs	93%	88%
	Foundation repairs	7%	9%
	Rebuild or relocate	0	3%

"The biggest impact that permafrost thaw has had on me is probably my house shifting, and that's... the foundation is still sound. But my drywall, especially around my windows, has cracked. And actually, a window on my north side of my house has cracked twice. So, we've replaced it twice... due to shifting of the house. Yeah, it's—that's how much it has moved.... And it's not too bad where I am, right? So, there is people that are, you know, drilled, their piles are right in bedrock. But I think mine has a little bit of ground until it reaches bedrock.... But yeah, the insurance doesn't cover it, and how I just deal with it, I just make the repairs."

—Nunavut participant (Firelight 2022)

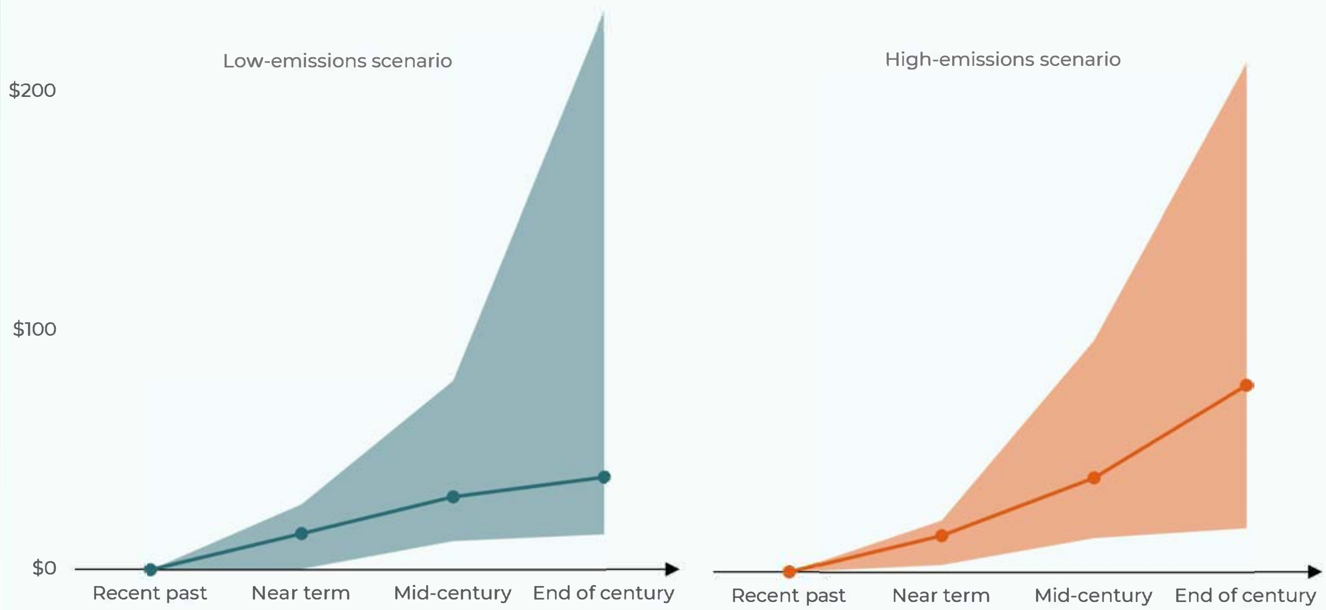


Arviat, Nunavut. Photo: Dylan Clark.

Figure 10

Costs from damages to buildings will rise across the North

Projected annual costs of building damage in millions of dollars (2019 CAD)



that faster warming and permafrost thaw under the high-emissions scenario will cause a more rapid increase in costs and damages than under the low-emissions scenario (Figure 10). Under the high-emissions scenario, near-surface permafrost in many areas will thaw entirely by the end of the century, resulting in an eventual decrease in costs and damages in some regions. On average, however, damages and costs throughout the North will continue to increase through the century.

Nunavut and the Northwest Territories will see the greatest overall impacts and costs because they have the most homes and buildings built on permafrost. All other Northern regions have very few buildings on permafrost.

Building adaptations could prevent costs and damages

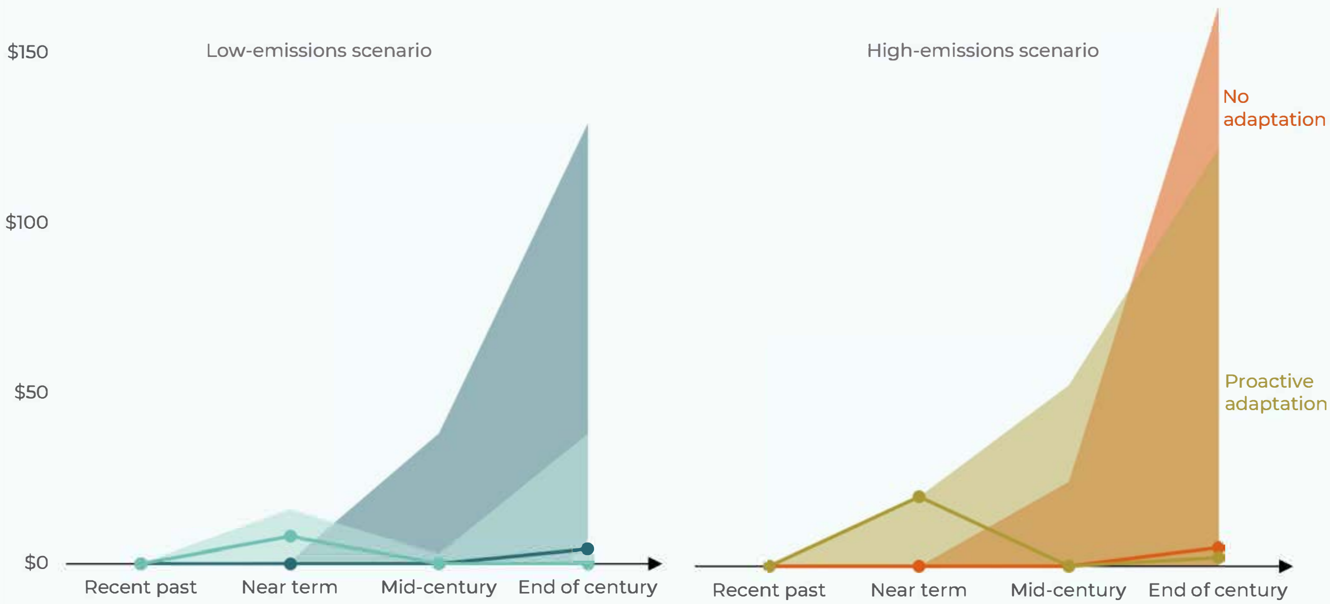
Adapting buildings, including homes, to permafrost thaw by installing thermosyphons can prevent critical foundation failures and reduce the need for repairs (see Box C).

Our analysis shows that using thermosyphons in targeted ways can significantly reduce costs. We modelled thermosyphons for buildings with projected critical foundation damage where the only foreseeable solution is rebuilding. Across the North, this adaptation can provide direct savings of $127 million and reduce damage costs by

Figure 11

Adaptation can prevent damages and reduce costs of permanent thaw for buildings in Nunavut

Projected annual costs of building damage in millions of dollars (2019 CAD)



78 per cent this century in a low-emissions scenario and save $33 million and reduce damage costs by 33 per cent in a high-emissions scenario.

In Nunavut, for example, adaptation could be particularly effective at reducing damages to buildings, if measures are implemented in the near term (Figure 11). Under the low-emission scenario, reconstructing buildings and installing thermosyphons could significantly reduce the risk of worst-case costs—the maximum projected costs of damage to buildings—in many areas. In a high-emissions scenario, more investments in adaptation will be needed to prevent critical damages because of rapid temperature increases. Even if adaptations are implemented in the near term, in the high-emissions scenario the costs of adaptation will initially exceed the costs of maintenance and repairs; however, by the end of the century adaptation will reduce the median costs of damage from permafrost thaw by 52 per cent.

High-tech adaptations such as the installation of thermosyphons may not be cost effective in some areas. Other incremental adaptations (which are outside the scope of our analysis) such as reinforcing foundations with pilings or using space-frame scaffolding to support buildings may be more cost-efficient solutions. In areas at high risk of permafrost thaw, adaptations such as pre-thawing permafrost, scaffolding foundation designs, and planning for infrastructure failure may be better long-term investments.

Adaptation to protect homes and community buildings from permafrost thaw provides benefits to health, well-being, and culture

Permafrost thaw can threaten the safety and diminish the viability of homes and community buildings. The first sign of permafrost thaw is often doors and windows not closing properly. Unless the foundation is levelled or the rate of thaw reduced, this damage can cause the whole structure to become unstable or even collapse. Damage from permafrost thaw also has knock-on effects on heating, moisture, and pipes. Cold air incursions and the formation of mould can have negative impacts on indoor air quality and health. Adaptations such as thermosyphons (discussed above), can slow permafrost impacts on homes and community buildings and protect the health and well-being of people.

The North already faces an acute shortage of adequate housing. Even without the added pressure of climate change on buildings, the inflated cost of construction, labour, and transportation has created a shortage of housing stock and a backlog of housing repairs. In Nunavut, 3,500 public housing units are needed to eliminate overcrowding—equivalent to 30 per cent of the existing 11,500 dwellings in the territory (ITK 2019; NTI 2020). Additional damage to existing housing from permafrost thaw will make addressing this deficit even more challenging because the housing stock will need to increase at an even faster pace amid insufficient labour and construction equipment supplies in the region. Implementing adaptation measures to avoid damages could help curb this prevailing gap.

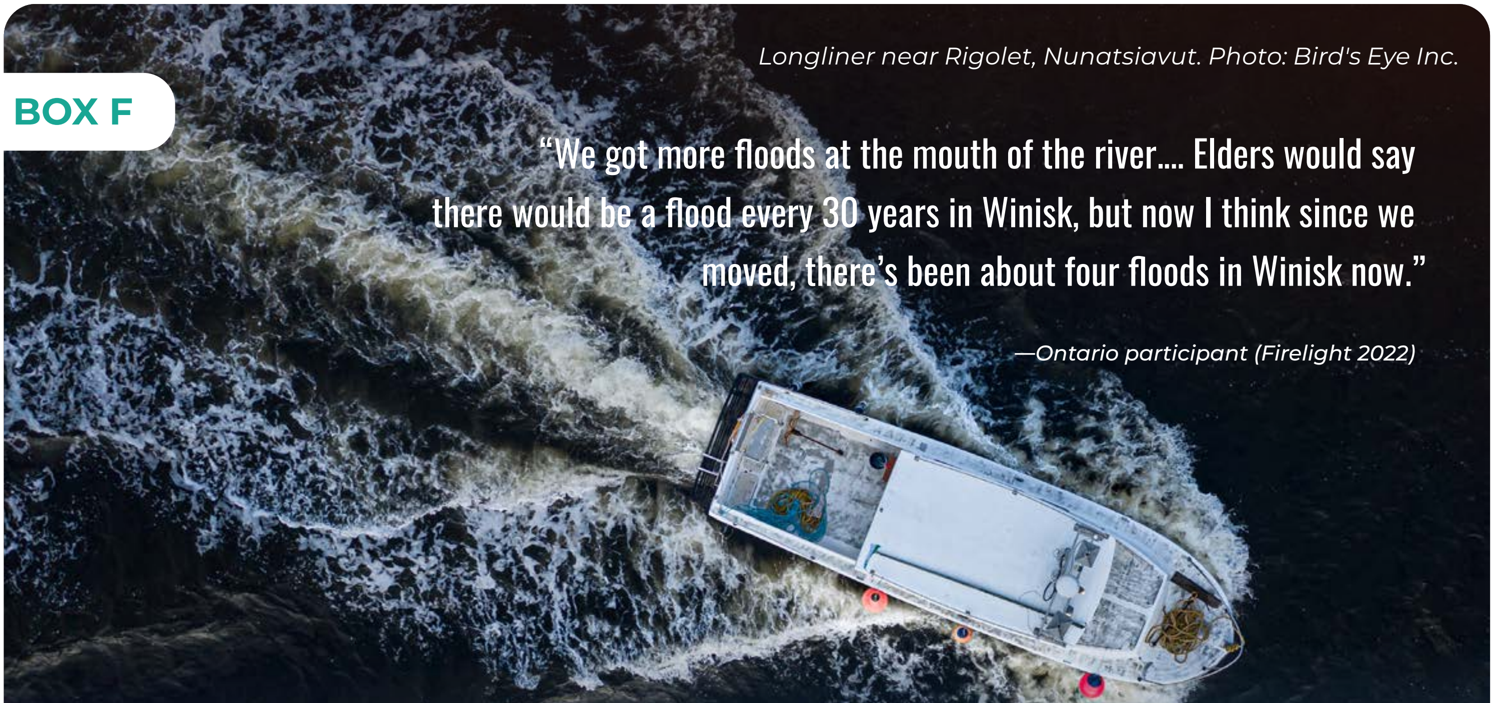
Community buildings provide vital infrastructure as places to share Indigenous knowledge and host community gatherings. Damage from permafrost thaw could pose a significant threat to these activities if public buildings become unusable due to damage to foundations. And, of course, permafrost is not the only climate-related threat to housing (Box F).

"When you look at housing and how expensive it is, I mean, there's no one thing that makes it expensive, it's all the, it's everything that makes it expensive. So, the pile driving, the import of material, import of the workforce. The [cost of] transportation has gone up significantly. So, building materials associated with fuel costs of transport. And when you just add all those things up, it just makes housing that much more unattainable."

—Nunavut participant (Firelight 2022)

Dawson City, Yukon.

BOX F



Longliner near Rigolet, Nunatsiavut. Photo: Bird's Eye Inc.

"We got more floods at the mouth of the river…. Elders would say there would be a flood every 30 years in Winisk, but now I think since we moved, there's been about four floods in Winisk now."

—Ontario participant (Firelight 2022)

Flooding is another hazard that threatens housing across the North

As temperatures rise, floods are projected to become more frequent, severe, and unpredictable in many places across the North.

Coastal communities in the Inuvialuit Settlement Region are seeing their shorelines retreat as sea levels rise, bringing hazards like storm surges closer to buildings (Hatcher and Forbes 2015). In other communities, rising temperatures are changing patterns of precipitation, ice break up, and snowmelt, resulting in floods that threaten buildings, roads, and drainage infrastructure (Lamoureux et al. 2015).

We analyzed the number of buildings at risk of inland flooding in Northwest Territories, Nunavut, Yukon, and Nunavik (Table 6). We used publicly available building and flood data from JBA Risk Management—data that are frequently used by the insurance industry to evaluate the flood risk of policy holders. Of the regions we analyzed, we found that Yukon has the highest percentage of buildings (including homes) in a present-day 100-year floodplain for inland flooding, followed by Northwest Territories. More information about flood costs across the North can be found In the Institute's *Under Water* report (Figure 12).

Table 6:

Percentage of buildings at risk of flooding according to insurance industry data

Region	Total Buildings	Percentage in 100-year flood zones
Northwest Territories	13,235	13%
Nunavik	29,530	7%
Nunavut	2,788	6%
Yukon	12,219	17%

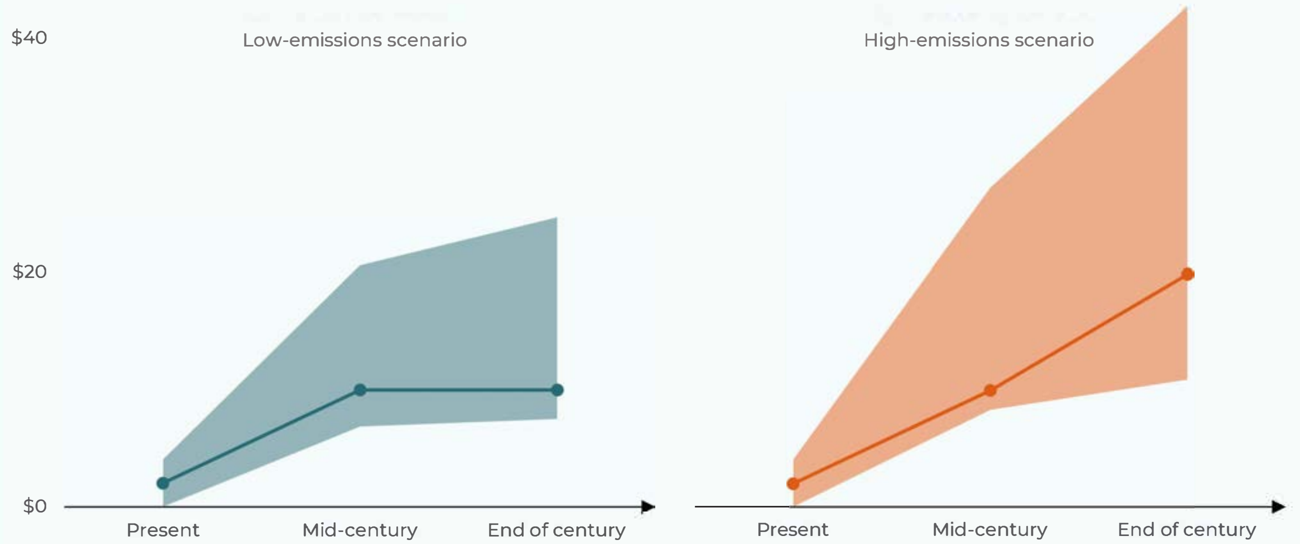
Floods and sea level rise could damage housing, which is already in short supply in many communities, as well as sites of historical and cultural significance for Indigenous Peoples, like Herschel Island in Yukon (Radosavljevic et al. 2016). Although sea level rise is not a risk for many communities, there are a handful of low-lying communities that are extremely exposed. Communities like Tuktoyaktuk and Ulukhaktok are at risk of complete costal inundation given that they are on thawing permafrost, potentially requiring hundreds of millions of dollars for coastal protection or managed retreat.

Across Canada, flood risk is poorly understood. The deficit of accurate flood risk information across the North presents a significant obstacle for adaptation. Maps are limited and out of date, and rarely consider the impacts of future climate change (Ness et al. 2021). This data gap is even more pronounced in the North (see Figure 4). Communities across the North will need accurate, up-to-date flood hazard data to better prepare for and adapt to the potential impacts to infrastructure.

Figure 12

Inland flood damage could increase rapidly across the territories

Projected annual costs of inland flooding in millions of dollars (2019 CAD)



Arviat, Nunavut. Photo: Dylan Clark.

7

NORTHERN PERSPECTIVES ON CLIMATE IMPACTS

Numbers only tell part of the story. In this section we explore key concerns related to Northern infrastructure and adaptation that emerged from Firelight's community-level research and from our engagement sessions with rights holders and stakeholders. We also draw on literature to expand on Firelight's findings and explore a broader geographic scope.

Engagement with stakeholders and decision makers is a part of the process of every major research project at the Climate Institute. Engagement has been particularly important for this report, because the experiences of Northern rights holders and stakeholders with infrastructure and climate change are different than those in the rest of Canada. It was important for us to learn from rights holders, stakeholders, and experts who are living with and dealing with the impacts of climate change on infrastructure to understand more about the problem and about potential solutions.

This summary cannot do justice to all communities' experiences. While we had discussions and received feedback from all territorial governments and many Indigenous governments, we were not able to engage with all Indigenous governments across the North. Furthermore, the Firelight Group's qualitative research could only reflect a small segment of perspectives and knowledge of the North's diverse Indigenous Peoples and communities.

Northerners with whom we engaged noted that the North is not uniform—its landscapes, cultures, histories, and governance are diverse. The functions that infrastructure such as roads, airports, and buildings serve differ significantly from region to region. Governmental roles and responsibilities regarding infrastructure and climate change adaptation also vary widely among regions. Regional economies are different from east to west across the North, and the private sector plays a much larger role in building and maintaining infrastructure in some places than others. Policies and actions that address infrastructure needs and climate change risks will therefore need to be attentive to regional differences.

What follows are four themes that emerged strongly from our research and engagement.

Northern Indigenous and municipal leaders are concerned about the cascading impacts of climate change on more than just infrastructure

Food security is an already visible impact of climate change and is a growing concern for Northern leaders. Firelight's work describes the effects that permafrost damage to transportation infrastructure can have on the availability and cost of store-bought food. Northerners have identified that shorter seasons for winter roads mean that in many communities, store-bought food and supplies have to be brought in by air, driving up food prices (Human Rights Watch 2020).

For Indigenous Peoples, climate change is also increasingly affecting the availability of country food (meat, fish, and berries) and the safety of travel across the land and sea ice (Ford et al. 2019; Neufeld and Richmond 2017; Naylor et al. 2021). Researchers have found that impacts on transportation systems and buildings inflict knock-on damage to country food systems. Although country food harvesting practices vary across the North and among First Nations, Métis, and Inuit communities, most people depend on snowmobiles, ATVs, and boats to participate in these subsistence activities. They also rely on sea lifts, roads, and airports to bring in fuel, equipment, and parts to enable them to spend time on the land. Fuel shortages or disruptions to sea lifts reduce access to country food (Clark et al. 2016).

Permafrost thaw is also affecting how people store and share food. Many people use underground food cellars dug into the permafrost to keep food frozen during the summer. As one participant from Inuvialuit describes, Northerners are increasingly relying on generators and electrical appliances to keep food cool. Food sharing networks—an important practice that helps feed communities and strengthen social ties for Inuit and many First Nations and Métis communities—are being disrupted by road outages, flight interruptions, and challenges for food storage.

> **"Up until a couple of years ago, I mean, we had an [underground] ice cellar at our cabin.... Well, we got two, we got one in the Mackenzie Delta cabin, and we clean that out every few years, add fresh snow. And the one at the coast is actually unusable anymore because it keeps accumulating water.... Even though we had it boxed in, insulated. It just couldn't keep food frozen anymore, or to a certain temperature, just because of the fluctuation of the temperature."**
>
> *—Inuvialuit Settlement Region participant (Firelight 2022)*

Northern Indigenous governments, municipalities, and some territorial governments noted that, in fact, direct costs of repairing and replacing infrastructure are only a small subset of the total costs of climate-related infrastructure impacts. Indirect costs from damaged or inadequate infrastructure, including business disruption, healthcare costs, and impacts to productivity, could be even more expensive. Additionally, many associated impacts, such as food insecurity and lost access to places of cultural significance, cannot be assigned a dollar value at all. To better manage both the indirect and incalculable costs, people described a need for governments to move beyond traditional cost/benefit analysis (Samson 2021).

Northern governments are having trouble accessing the funding, resources, and capacity needed to improve and adapt infrastructure

We heard that federal infrastructure funding programs are not designed in a way that Northern (territorial, Indigenous, and municipal) governments can access them. Cost sharing arrangements are a significant barrier for Indigenous and territorial governments, particularly when money is required up front to develop proposals or conduct feasibility studies. Many Indigenous and territorial governments do not have the capacity to develop extensive funding proposals or work through lengthy application processes. Program timelines for design and implementation do not reflect the realities and importance of Indigenous engagement, the short season for Northern construction, or limited government capacity. As a result, Northern governments often miss out on much-needed infrastructure funding, or they lose out in competitive funding programs where they are up against larger provincial governments or southern municipalities.

Northerners also told us that funding programs rarely promote development of Northern capacity and retention of technical skills (for example, construction, engineering, mechanics, planners). Historically, infrastructure funding has not been stable or predictable, meaning that when funding dries up, skilled jobs disappear. Northerners with technical training and skills often find it difficult to secure stable employment in the North in their field. As a result, when cyclical federal funding is available, the technical skills sometimes aren't, meaning labour must be imported from the south, which makes infrastructure projects more expensive due to travel costs.

The municipalities and Indigenous governments we engaged with suggested that federal, provincial, and territorial governments do not consistently involve them in prioritizing infrastructure investments and developments. Furthermore, local and Indigenous knowledge is not always reflected in infrastructure design, resulting in infrastructure designs that are often less suited to local and cultural needs and are more vulnerable to climate-related hazards.

Territorial governments we engaged with expressed that the federal government does not consistently involve them in infrastructure prioritization and funding decisions. Examples raised include the development of relevant strategies and policy frameworks and the design of funding calls and strategic infrastructure projects.

Many people we engaged with noted that climate change poses unique risks in Northern Canada, including permafrost thaw, sea level decreases (in the Hudson Bay region), and winter road access.

Because hazards and vulnerabilities are different in Northern Canada than southern Canada, the climate risk information needed to support adaptation is different. Many territorial governments, municipalities, and Indigenous governments do not currently have the resources required to produce climate data relevant to them. Existing climate data is seldom downscaled (calculated for local levels) for the North, so it is difficult to assess community-level risks. This means that people, businesses, and governments are often unaware of potential climate risks to infrastructure. Furthermore, infrastructure codes, standards, and design practices do not always reflect Northern climate change risks.

Northern innovation is already driving new approaches

Indigenous Peoples and other Northerners have always adapted to environmental changes, and they are adapting to the climate changes already occurring in the North (Wenzel 2009; Ford et al. 2015). As one participant from Ontario describes, Northerners are gardening and growing food locally to reduce their reliance on expensive, shipped-in and store-bought food (Ritchie 2021). Others are changing their patterns of hunting and harvesting on the land, trying new locations and different times of year.

Researchers and Inuit have found that technology and equipment (such as GPS devices or ice-monitoring equipment) can help people continue to spend time on the land safely (Aporta et al. 2005; Clark et al. 2016). People also share information about environmental changes through their community networks and ties (Fox et al. 2020; Bell et al. 2014). These adaptations could be better supported and resourced by governments, such as through harvester support programs, improved weather monitoring, and facilitating information-sharing in culturally appropriate ways (Clark et al. 2016).

Northerners are rethinking how critical services are delivered to adapt to climate change impacts and challenges. To overcome barriers around healthcare access across the North, for example, a team of physicians and researchers has been developing tools to provide remote high-quality medical care. Trials have included the use of remote-controlled robots to assist with patient assessments (Jong et al. 2019; Adams et al. 2021; Ellis et al. 2020).

Northerners are also rethinking the design of infrastructure to make it more resilient and appropriate for their needs. For example, in close collaboration with Inuit stakeholders, a team of researchers and architects has been exploring how Northern airports and buildings are designed (White et al. 2010). One conceptual design of airports in Nunavut integrates the community health centre with the airport in recognition of the importance of air travel to Northern healthcare (White et al. 2010). The team has also proposed new ways of thinking about Elder care centres in order to re-centre Inuit culture and holistic approaches to well-being into building design (Lola Sheppard et al. 2017).

> "I'm experimenting with gardening, so we don't have to buy our food from California or Mexico.… And it's kind of a—I have to have a science to it because everything up here is peat, … and you just can't grow anything.… And then next year I'm buying chickens, so we don't have to buy eggs."
>
> —*Ontario participant, (Firelight 2022)*

Successful adaptation requires transformative shifts that address root causes of infrastructure vulnerability

From industry representatives to the public sector to Indigenous governments, we heard frequently that transformative changes will be needed in order to address the infrastructure gaps in the North and protect people and communities from climate hazards.

Education and skill training is one key area where transformative changes may be needed to build resilience and address the infrastructure gap. We heard that access to both technical and higher educational programs are limited in most communities. Until Yukon College became Yukon University in 2020, there was no university in the North. In Nunavut, students only have access to university education through partnerships with universities outside the region (NTI 2020). Online and remote education is an emerging option, but slow internet speeds prevent many Northerners from accessing online education opportunities.

Researchers and Northerners have observed that education and skills gaps often result in industry and governments importing labour from the south, limiting capacity to build and maintain infrastructure in the North. Unpredictable federal infrastructure spending and boom-and-bust sectors like mining perpetuate the skills deficit, as the skills and certifications required to build and repair infrastructure are difficult to sustain in many Northern communities. Underinvestment in education infrastructure (including schools, high-speed internet, and water and food security) further exacerbates this cycle by increasing the barriers to training.

Rights holders and stakeholders also identified other important root causes of infrastructure gaps and climate change vulnerability, such as immediate health crises taking up government bandwidth, high turnover of staff in some Northern governments, and a small economic tax base. Many of the root causes identified speak to the ongoing impacts of colonialism and racism.

Pond Inlet, Nunavut. Photo: Dylan Clark.

8

CONCLUSIONS AND RECOMMENDATIONS

With the North warming at an accelerated rate, climate change is already impacting the lives of Northerners through infrastructure failures and service disruptions. Historic and present-day policies have placed Northern communities at a major disadvantage in preparing for and adapting to climate impacts. For Indigenous Peoples, this disadvantage is further underscored by legacies of colonialism, southern paternalism, and racism.

It is time to give the North its due. Our analysis shows that all orders of government need to set policies and make investments without delay to prepare for the impacts of climate change on Northern infrastructure.

Photo: Bird's Eye Inc.

Conclusions

Five overarching insights emerge from our assessment of climate impacts on Northern infrastructure.

1 Without specific and targeted interventions, climate change will further widen the existing gaps in basic infrastructure service across the North

Even leaving aside future climate change impacts, insufficient infrastructure means that Northerners—especially Indigenous Northerners—already lack access to essential services.

There are enormous financial, cultural, health, and well-being costs when infrastructure fails in the North, and, as our analysis shows, Northern infrastructure failures will accelerate as the climate continues to change. Our modelling showed that the direct costs of this damage could amount to billions of dollars in damage to airports, roads, and buildings alone over the next three decades. We also highlight that there are many other costs that cannot be modelled but that could bring even larger costs and damages. Shortages in safe and affordable housing across the North exacerbated by climate change, for example, could lead to major health impacts. Climate-induced damage to airport infrastructure can threaten people's ability to access emergency medical care.

Even without climate change, the Northern infrastructure gap is self-reinforcing. For example, a lack of ports, roads, and airports to bring in construction supplies drives up the cost of shipping materials to build and maintain infrastructure. A lack of education facilities means that few Northerners have the technical skills to work on infrastructure development—and the housing crisis makes it difficult and expensive to bring in southern labour. Closing the Northern infrastructure gap requires immediate and ongoing investment in resilient infrastructure. Otherwise, the gap will continue to grow, worsening the inequity in infrastructure service delivery between Northern and southern communities and making it even more costly to build functional infrastructure in the years ahead.

Neither the Northern infrastructure gap nor the climate threat to Northern infrastructure can be solved alone—each reinforces the other, and so both must be addressed together. Investments in adaptation can close the Northern infrastructure gap by designing, locating, and building infrastructure that is functional, reliable, and resilient in a warming climate.

2 Northern Indigenous Peoples face unique and elevated threats from impacts of failing infrastructure

In the North, Indigenous Peoples have adapted to their changing environment since time immemorial and have exhibited extraordinary resilience in the face of colonization and dispossession. But the climate is changing more rapidly now than any previous generation has experienced.

Colonization and racism have deeply affected the adaptive capacity of Indigenous Peoples across the North in the face of infrastructure failures and deficits. Historically, governments designed social and economic policies to destroy Indigenous cultures, deeply damaging the social fabric, knowledge, and institutions that are essential for climate change adaptation (Truth and Reconciliation Commission of Canada 2015). Years of systemic underinvestment and southern neglect have undermined Indigenous health, well-being, and culture. And countless Northern policies and programs have systematically excluded the input of Indigenous Peoples, resulting in infrastructure that does not reflect their values, cultures, or the reality of their lives.

To this day, infrastructure decision making processes often do not involve the full participation of Northern Indigenous rights holders and governments. The lack of Northern Indigenous participation continues to affect the way funding programs are designed and the prioritization of infrastructure that fails to meet people's most immediate needs.

3 Northern infrastructure failures due to climate change will prove costly and put critical services at risk

Northern infrastructure is increasingly exposed to the impacts of climate change. Runways and roads are cracking from permafrost thaw, winter roads are becoming unsafe or impossible to build, building foundations are breaking apart, and sea level rise and flooding are threatening the very existence of some Northern communities.

When Northern infrastructure is damaged or destroyed, it puts critical services at risk. Infrastructure systems are uniquely sensitive to climate change impacts across the North because there is frequently no backup and because services are already chronically deficient. When one piece of infrastructure fails—such as a diesel power station outage or damage to a runway—it can quickly sever healthcare delivery and access to food.

Northern infrastructure failures are also costly. This is in part because the direct costs of replacing and repairing infrastructure in the North can be many times the costs in southern Canada. But damage to Northern infrastructure is also more costly due to broad, cascading impacts and disruptions. These cascading impacts and costs were on full display in the City of Iqaluit in 2021, when the city's water supply was contaminated with fuel. This multi-month emergency not only disrupted drinking water access for most of the town, but also caused surgeries to be delayed at the hospital and affected food availability.

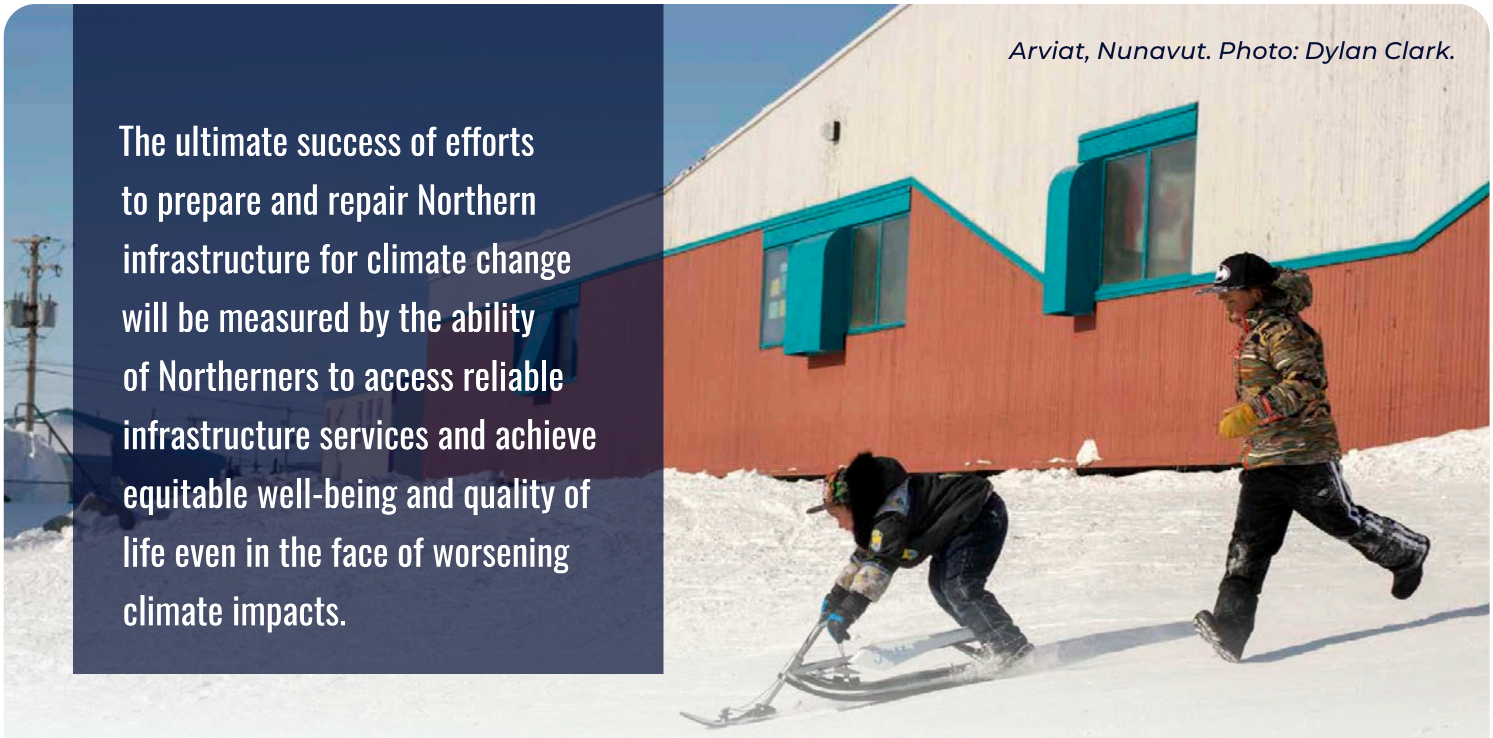
4 A lack of co-ordination between multiple orders of government is undermining infrastructure resilience

All orders of government have a role in setting policy and taking action to reduce the risk of critical service failures. To date, there is no framework that self-governing Inuit and First Nations governments, territorial governments, and the federal government have agreed on to support infrastructure and climate change adaptation decisions. Instead, different orders of government have inconsistent and uncoordinated infrastructure strategies and adaptation initiatives.

5 Incremental adaptations alone are insufficient to safeguard infrastructure services against climate change

Given both the current Northern infrastructure gap and the pace of climate change impacts, transformative adaptations can sometimes offer larger returns than incremental adaptations alone. Our analysis shows that incremental adaptations can slow or delay costs in some cases but often only prolong inevitable infrastructure failure.

Transformative adaptations are a clear opportunity to fundamentally change infrastructure systems that are no longer working—or have never worked—for Northerners and Indigenous Peoples by leapfrogging to new infrastructure technologies that deliver better, more appropriate, and more resilient services. However, transformative adaptation is not yet a part of mainstream thinking about climate change adaptation in the North.



Arviat, Nunavut. Photo: Dylan Clark.

> The ultimate success of efforts to prepare and repair Northern infrastructure for climate change will be measured by the ability of Northerners to access reliable infrastructure services and achieve equitable well-being and quality of life even in the face of worsening climate impacts.

Recommendations

Climate change is a massive threat to Northern lives, livelihoods, health, and security. The best way to minimize that threat is through a co-ordinated approach to both closing the Northern infrastructure gap and bolstering Northern infrastructure resilience. There is a clear opportunity to realign Northern infrastructure policies with the collective vision of Canada's Arctic and Northern Policy Framework—"strong, self-reliant people and communities working together for a vibrant, prosperous, and sustainable Arctic and northern region" (CIRNAC 2019). The ultimate success of efforts to prepare and repair Northern infrastructure for climate change will be measured by the ability of Northerners to access reliable infrastructure services and achieve equitable well-being and quality of life even in the face of worsening climate impacts. Failure to adapt, on the other hand, could lead to rapidly growing costs for the North and for Canada as a whole—not only from infrastructure damage and destruction but also from impacts to community and individual health and ways of life.

Moving forward, new infrastructure should be built across the North to fill service gaps, keep pace with growing populations, prepare for climate hazards, and respond to geopolitical changes. And because historically, infrastructure in the North has not been built for the needs of Indigenous Peoples, infrastructure decisions, economic development processes, and climate change adaptation strategies moving forward must respect Indigenous Peoples' right to self-determination.

We outline four recommendations that will help build resilience in the North through better infrastructure decisions. Because colonization and racism are key root causes of climate change infrastructure vulnerability, all four recommendations are rooted in a guiding principle of self-determination and should be implemented through that lens.

GUIDING PRINCIPLE:

All infrastructure development and adaptation policies should be implemented **in a manner that is consistent with the principles outlined in Canada's Truth and Reconciliation Report.**

Federal, provincial, and territorial governments should engage Indigenous governments and communities in equal partnership to ensure Northern Indigenous communities have reliable and equitable infrastructure services that meet their expressed needs.

Climate change adaptation is an opportunity to renew and transform Northern infrastructure so that it better serves Indigenous Peoples. Federal, provincial, and territorial governments must develop infrastructure through more equitable and collaborative processes, working closely with self-governing Indigenous governments and regional Indigenous organizations.

By definition, Indigenous governments and communities—each with distinct and diverse needs and priorities—must have power over how infrastructure decisions are made. Federal, provincial, and territorial governments must therefore listen to, engage with, and follow the lead of Indigenous governments and communities from the initiation of infrastructure projects across the North through to their construction, operation, and ongoing adaptation.

Pangnirtung, Nunavut. Photo: Dylan Clark.

1. FUNDING: The federal government should dedicate new financial resources for Northern infrastructure and restructure existing infrastructure funding programs to increase accessibility and usefulness to Northern governments.

Existing infrastructure funding programs are not working for Northern (territorial, municipal, regional, and Indigenous) governments as they do not reflect the physical, economic, or social realities of building and maintaining infrastructure in the North. Timelines do not account for short building seasons or the complexities of transporting materials, application processes can overburden the limited capacity of local governments, and funding is intermittent. Furthermore, the amount of funding currently available to Northern governments is insufficient to close the Northern infrastructure gap, adapt existing infrastructure, and maintain current infrastructure, let alone to support measures to adapt infrastructure to a warming climate.

The federal government should dramatically restructure funding programs so that Northern governments can benefit from them. This requires:

- Funding that is stable and predictable with a multi-year horizon to align with infrastructure prioritization, planning, and construction timelines.
- Programs that provide funding for full-time jobs alongside capital funding to help fill Northern government capacity gaps.
- Greater flexibility in funding programs, including mechanisms like rollover funding and stacking. Territorial governments should also give municipalities the latitude to rollover infrastructure funding for multiple years to save funds for larger capital upgrades.
- Increased federal funding for existing Northern infrastructure programs and new funding programs to support climate adaptation of existing infrastructure.

2. INFORMATION: The federal government should support provincial and territorial governments in developing and maintaining accurate and practical information about Northern-relevant climate risks to infrastructure. This data should prioritize information that is important to Northern decision makers and Indigenous communities.

A lack of data on the climate risks that threaten Northern infrastructure makes it challenging to account for climate change in the design of new infrastructure or the adaptation of existing infrastructure. Northern (territorial, municipal, regional, and Indigenous) government lack detailed data about current and future climate- and weather-related risks to infrastructure such as roads, airports, buildings, utilities, and ports. This includes a lack of ongoing monitoring and projections of permafrost thaw, wildfires, changes to wind, and thunderstorms.

The federal government should provide the financial and technical support for the collection of data on changing climatic conditions and climate risks, and for projection of future risks. However, it is important that Northern and Indigenous governments have input into, and in some cases control over, how data is collected, modelled, downscaled, managed, and stored.

- The federal government should provide long-term funding that is stable and predictable to ensure that communities can track long-term climate-related impacts. Long-term climate data is essential to making cost-effective decisions about infrastructure. Climate and risk data that is not consistently tracked for many years has minimal utility.
- Funding should include education, training, and skills development so that communities can build capacity to monitor and collect the data they need.
- Provincial and territorial governments should work closely with Northern and Indigenous communities to determine their climate risk data needs and research priorities.
- Data should be at a scale that is relevant to Northern and Indigenous communities. This includes downscaling climate projections and detailed maps of climate change risk at the community level. Furthermore, governments should ensure that the data is accessible (both culturally appropriate and available with Northern internet) to Northerners.
- Climate information to support Northern adaptation should draw from western and Indigenous ways of knowing to benefit from the strengths of each (ECCC 2020).

3. INNOVATION: All orders of government should prioritize infrastructure replacement and transformative leapfrogging over repair and protection wherever this is a more effective, efficient, and sustainable way to safeguard services.

It is going to be challenging to keep up with the speed at which climate change impacts infrastructure across the North, even with additional resources. Permafrost thaw is affecting more buildings, winter roads are quickly becoming inoperable, and transportation systems are not able to deliver the services that people depend on.

To deliver the best infrastructure services possible with limited resources, all orders of government will need to make data-informed infrastructure decisions—including developing infrastructure asset management systems that consider climate change in long-term operations, maintenance, and replacement decisions (Federation of Canadian Municipalities 2018). This includes identifying where existing infrastructure can be adapted to reduce the cost and disruption of frequent repairs, but it also includes identifying existing infrastructure that is no longer worth repairing or protecting in the face of accelerating impacts from climate change. In such cases, it may be both more cost-effective and less disruptive to build replacement infrastructure that is designed for future climate conditions rather than to continually repair current infrastructure that is not.

- Territorial and federal governments should increase the use of incremental adaptations (for example, thermosyphons, embankment cooling, and base-layer reinforcement) to protect infrastructure from permafrost thaw and other climate changes. However, decisions to use incremental adaptations should consider long-term costs and benefits and, if implemented, should be monitored to determine when they are no longer cost-effective.

- Governments should seek out opportunities for transformative adaptation by developing next-generation infrastructure systems that leapfrog historical infrastructure models. Such opportunities might include investing in renewable microgrids—instead of rebuilding a diesel plant—to help close electricity service gaps and make Northern communities more resilient to less reliable roadways for shipping fuel, or improving remote presence and tele-health to reduce reliance on planes and airports to fly patients south to see specialists.
- In select cases, planned failure or managed retreat may be the most cost-effective option because the cost of maintaining current infrastructure in present locations can be far more expensive than rebuilding elsewhere or delivering services by other means. It is essential that Northerners make these decisions. In circumstances where planned failure is deemed the best course, there may be prime opportunities for transformative adaptation.

4. REGULATION: The federal, provincial, and territorial governments should update infrastructure policies, regulations, standards, and codes to explicitly account for the more complex and severe impacts of climate change in the North and to ensure that new infrastructure is resilient.

Infrastructure across the North is still being built for yesterday's climate. In the coming years, a great deal of new infrastructure will need to be built in the North to ensure people have access to basic services like clean drinking water, housing, and access to medical care. Regulatory changes can ensure this infrastructure is built to withstand future climate change.

- Internal government decision making and legislative processes should include analysis of physical climate risks. For example, governments and regulatory bodies should ensure that environmental impact assessments include physical climate risk disclosures. Governments should account for future flood, sea level rise, and permafrost thaw risks in their land use planning. They should also integrate physical climate risks into capital infrastructure planning processes and investment decisions, such as flood and permafrost risk analysis of all large infrastructure projects.
- Territorial and provincial governments should develop clear plans to mandate use of standards and codes, such as those developed under the Northern Infrastructure Standardization Initiative, for all public and private infrastructure that provides critical services.
- Standards, codes, and regulations should reflect the best available climate data and should be informed by both western and Indigenous knowledge systems.
- Governments should apply adaptive management for codes and standards updates to ensure that regulations keep pace as understanding of climate change risks continues to improve.

GLOSSARY

Adaptation: Actions that reduce damage and loss from actual or expected climate change, while taking advantage of potential new opportunities.

Adaptive capacity: The strengths, attributes, and resources available to an individual, community, society, or organization that can be used to adapt to climate change.

Base layer reinforcement: A method that involves building embankments with multiple layers of permeable fabrics that help to reinforce, protect, and drain soil, helping infrastructure resist the structural consequences of permafrost degradation

Climate: The average weather in a place over an extended period, typically 30 years or longer.

Climate change: Changes in the Earth's climate, predominantly caused by the burning of fossil fuels, that add heat-trapping gases to Earth's atmosphere. It manifests as overall global warming but also in sea level rise, melting of previously permanent snow and ice fields, and more extreme weather.

Climate model: A climate simulation based on well-documented physical processes. Climate models, also known as general circulation models (GCMs), use mathematical equations to characterize how energy and matter interact in different parts of the ocean, atmosphere, and land.

Climate projections: A simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission, concentration, or radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Climate-related hazards: The potential occurrence of a climate-related physical event that may cause loss of life, injury, or damage and loss to property, infrastructure, service provision, and environmental resources. Due to climate change, frequencies of some hazards are expected to continue to increase.

Colonialism: The practice of acquiring full or partial political control over another nation, occupying it with settlers, and exploiting it economically. In Canada, colonialism is an ongoing process that continues to have destructive impacts on Indigenous Peoples' education, cultures and languages, health, child welfare, the administration of justice, and economic opportunities and prosperity.

Embankment cooling: Practices used to protect permafrost from thawing underneath road infrastructures. Embankment cooling often refers to air cooled embankment (ACE) which uses highly porous materials such as boulders or cobble to construct the embankment of roads. Removing snow from the side of the roads, runways, or building pads during winter months further prevents thawing by allowing the air to cool surface grounds.

Exposure: The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected by climate change.

Impacts: Effects on natural and human systems. In this report, the term is used to refer to the effects on natural and human systems of physical events, disasters, and/or climate change.

Incremental adaptation: An adaptation strategy that aims to protect and preserve existing systems. Common examples include physical risk disclosure regulations, flood walls and dikes, and fire suppression. In the case of infrastructure, incremental adaptations focus on preserving existing infrastructure systems as opposed to innovative new ways to deliver services (see ***transformative adaptation***)

Indigenous knowledge holders: Individuals who encompass generations of knowledge embedded within the unique cultures, languages, governance systems, and experiences of Indigenous Peoples.

Infrastructure gap: In this report, the term infrastructure gap is used specifically to refer to the infrastructure deficit in Northern Canada when compared to southern Canada. The Northern infrastructure gap results in inadequate stock of infrastructure in the North, sparse and unequal investments in infrastructure, and unequal access to infrastructure services—especially when compared to southern Canada.

Inuit Nunangat: The Inuit homeland, encompassing the four Inuit regions of Canada: the Inuvialuit Settlement Region, Nunavut, Nunavik, and Nunatsiavut.

Leapfrog: When a nation or region bypasses traditional stages of development to either jump directly to the latest technologies or take an alternative path of development involving emerging technologies or knowledge with new benefits and new opportunities.

Managed retreat: A strategic relocation of people, structures, and buildings in the face of natural hazard risks. Managed retreat often occurs in response to sea-level rise, floods, and wildfires. But it can also involve a strategic abandonment of land to allow for natural environments to be re-established.

Northern Canada: Yukon, Northwest Territories, Nunavut, Nunavik, and Nunatsiavut, as well as the northern regions of British Columbia, Alberta, Saskatchewan, Manitoba, and Ontario. The northern regions of provinces have been defined as land north of 55 degrees of latitude. In this report, Northern Canada is used primarily to refer to areas that currently have permafrost. However, we acknowledge that there are many different definitions of the North, that its cultures and ecosystems are diverse, and that traditional land use and occupancy of Indigenous communities are not limited to these bureaucratic boundaries.

Northerner: Resident of the North. This term is inclusive of both Indigenous Peoples living in the North as well as settlers.

Permafrost: Ground that remains below zero degrees Celsius for at least two consecutive years.

Planned failure: An adaptation approach where asset managers strategically allow infrastructure to fail and become unserviceable. Prior to infrastructure being decommissioned asset managers build an alternative and more resilient means of delivering services.

Resilience: The ability of a physical, social, or ecological system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a disaster in a timely and efficient manner.

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain. Risk is often represented as probability of the occurrence of hazardous events or trends, multiplied by the potential impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard. In this report, the term risk is used primarily to refer to the risks of impacts related to climate change.

Self-government: The formal structure through which Indigenous communities control the administration of their people, land, resources, and related programs and policies. Self-governance recognizes the inherent rights of Indigenous Peoples to maintain and implement their own institutions, laws, and governing bodies.

Thermosyphons: Refrigeration devices designed to keep permafrost cold by drawing heat from the ground and releasing it into the air. Typically, thermosyphons are sealed pipes containing a pressurized fluid that is partly liquid and partly gas. The tubes are installed vertically, with one end below ground and the other above ground.

Transformative adaptation: An adaptation strategy that aims to reduce the root causes of vulnerability to climate change in the long term. Transformative adaptation is often characterized by system-wide changes in anticipation of climate change and its impacts. In the case of infrastructure, transformative adaptations focus on innovative ways to deliver services as opposed to preserving existing infrastructure systems (see ***incremental adaptation***)

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, negative effects of climate change, including climate variability and extremes.

Winter road: A seasonal road only used in winter—and manually rebuilt each year—that typically crosses land, frozen lakes, and rivers.

REFERENCES

Adams, Scott J., Paul Babyn, Brent Burbridge, Rachel Tang, and Ivar Mendez. 2021. "Access to Ultrasound Imaging: A Qualitative Study in Two Northern, Remote, Indigenous Communities in Canada." *International Journal of Circumpolar Health* 80 (1). https://doi.org/10.1080/22423982.2021.1961392

Allard, Michel, Mickaël Lemay, Carl Barrette, Emmanuel L'Hérault, Denis Sarrazin, T. Bell, and G. Doré. 2012. "Permafrost and Climate Change in Nunavik and Nunatsiavut: Importance for Municipal and Transportation Infrastructures." In *Nunavik and Nunatsiavut: From Science to Policy. An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization*, edited by Michel Allard and Mickaël Lemay, 171–197. ArcticNet Inc.

AMAP (Artic Monitoring and Assessment Programme). 2019. *Arctic Climate Change Update 2019: An Update to Key Findings of Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. https://www.amap.no/documents/doc/amap-climate-change-update-2019/1761*

Aporta, Claudio, Eric Higgs, David Hakken, Lisa Palmer, Mark Palmer, Robert Rundstrom, Bryan Pfaffenberger, George Wenzel, and Thomas Widlok. 2005. "Satellite Culture: Global Positioning Systems, Inuit Wayfinding, and the Need for a New Account of Technology." *Current Anthropology* 46 (5): 729–753.

Arctic Council. 2016. *Arctic Resilience Report*. Edited by Marcus Carson and Garry Peterson. Stockholm Environment Institute and the Stockholm Resilience Centre. Stockholm. http://www.arctic-council.org/arr

Arnaquq-Baril, Alethea. 2016. *Angry Inuk*. National Film Board of Canada. Toronto, ON.

Baijius, Warrick, and Robert J Patrick. 2019. "'We Don't Drink the Water Here': The Reproduction of Undrinkable Water for First Nations in Canada." *Water* 11 (5). https://doi.org/10.3390/w11051079

Barrette, Paul D., Sean Ferguson, Vahid Pilechi, and Naveed Khaliq. 2018. *The Yukon River at Dawson City: Assessment of Factors Influencing Freeze-up and Ice Bridge Construction*. National Research Council Canada. Ottawa, ON. https://nrc-publications.canada.ca/eng/view/ft/?id=787e9ae1-15f2-4cf9-849d-801e0d4aa974

Barrette, Paul D., and Lawrence Charlebois. 2018. *Winter Roads and Climate Adaptation: Prospective Solutions through R&D*. National Research Council Canada. Ottawa, ON. https://nrc-publications.canada.ca/eng/view/ft/?id=1b84a91c-edb6-4640-ada1-0126dd04f2b0

Basky, Greg. 2021. "Equity in Focus: Iqaluit Water Contaminated, Tuberculosis on the Rise, Blood Ban Easing." *CMAJ* 193 (44): E1706–E1707. https://doi.org/10.1503/CMAJ.1095970

Bell, Trevor, Robert Briggs, Ralf Bachmayer, and Shuo Li. 2014. "Augmenting Inuit Knowledge for Safe Sea-Ice Travel—The SmartICE Information System." In *2014 Oceans-St. John's,* 1–9. https://doi.org/10.1109/OCEANS.2014.7003290

Boehlert, Brent, James E. Neumann, Jason Price, Charles Fant, Paul Chinowsky, Jacob Helman, Kenneth M. Strzepek, and Jacqueline Willwerth. 2021. *Costing Climate Change Impacts on Canada's Infrastructure.* Prepared for the Canadian Climate Institute (formerly Canadian Institute for Climate Choices).

Bouchard, Christina. 2020. *Arctic Airports and Aerodromes as Critical Infrastructure*. North American and Artic Defence and Security Network.

Brockman, Alex, and Randi Beers. 2018. "N.W.T. Gov't Commits to Airlifting Some Cargo Affected by Barge Cancellation." *CBC News*, October 5. https://www.cbc.ca/news/canada/north/nwt-barge-cancellation-airlift-1.4853166

Brooks, Heather, Guy Doré, and Chantal Lemieux. 2017. *Quantitative Risk Assessment of the Iqaluit International Airport, Iqaluit, Nunavut*. Transport Canada.

Brown, Daniel M., Bohdan Kochtubajda, and Ryan K. Said. 2020. "A Severe Thunderstorm Outbreak North of 70°N Over the Canadian Arctic Islands with Unusual Lightning Characteristics." *Atmosphere-Ocean* 58 (4): 231–242. https://doi.org/10.1080/07055900.2020.1792405

Bush, Elizabeth, and Donald S. Lemmen, eds. 2019. *Canada's Changing Climate Report*. Government of Canada. Ottawa, ON. https://changingclimate.ca/CCCR2019/

Castillo, Victoria Elena, Christine Schreyer, and Tosh Southwick. 2020. "Highways and Social Change." In *ECHO: Ethnographic, Cultural and Historical Overview of Yukon's First Peoples*. Institute for Community Engaged Research Press.

CBC (Canadian Broadcast Corporation). 2011. "Hercules Charter Means 'Christmas' in Old Crow." *CBC News*, February 28. https://www.cbc.ca/news/canada/north/hercules-charter-means-christmas-in-old-crow-1.1053336

References

CBC (Canadian Broadcast Corporation). 2015. "Teamwork Helps Pangnirtung Residents Pull through Power Outage." *CBC News*, April 11. https://www.cbc.ca/news/canada/north/teamwork-helps-pangnirtung-residents-pull-through-power-outage-1.3029395

Chen, Yang, David M Romps, Jacob T Seeley, Sander Veraverbeke, William J Riley, Zelalem A Mekonnen, and James T Randerson. 2021. "Future Increases in Arctic Lightning and Fire Risk for Permafrost Carbon." *Nature Climate Change* 11 (5): 404–410. https://doi.org/10.1038/s41558-021-01011-y

CIRNAC (Crown-Indigenous Relations and Northern Affairs Canada). 2019. "Canada's Arctic and Northern Policy Framework." Government of Canada. https://www.rcaanc-cirnac.gc.ca/eng/1560523306861/1560523330587

Clark, Dylan, and Anna Kanduth. 2022. *Enhancing the Resilience of Canadian Electricity Systems for a Net Zero Future*. Canadian Climate Institute (formerly Canadian Institute for Climate Choices). https://climatechoices.ca/wp-content/uploads/2022/02/Resiliency-scoping-paper-ENGLISH-Final.pdf

Clark, Dylan G., James D. Ford, Tristan Pearce, and Lea Berrang-Ford. 2016. "Vulnerability to Unintentional Injuries Associated with Land-Use Activities and Search and Rescue in Nunavut, Canada." *Social Science and Medicine* 169: 18–26. https://doi.org/10.1016/j.socscimed.2016.09.026

Coffel, Ethan D., Terence R. Thompson, and Radley M. Horton. 2017. "The Impacts of Rising Temperatures on Aircraft Takeoff Performance." *Climatic Change* 144 (2): 381–388. https://doi.org/10.1007/S10584-017-2018-9/FIGURES/3

Connor, Billy, Douglas J. Goering, Mikhail Kanevskiy, and Erin Trochim. 2020. *Roads and Airfields Constructed on Permafrost: A Synthesis of Practice*. https://dot.alaska.gov/stwddes/research/assets/pdf/000S927.pdf

CRTC (Canadian Radio-television and Telecommunications Commission). 2020. *Communications Monitoring Report, 2020*. Government of Canada. Ottawa, ON. https://publications.gc.ca/collections/collection_2020/crtc/BC9-9-2020-eng.pdf

Cruikshank, Julie. 1985. *The Gravel Magnet: Some Social Impacts of the Alaska Highway on Yukon Indians*. Vancouver, BC. https://trid.trb.org/view/231861

Debortoli, Nathan S., Dylan G. Clark, James D. Ford, Jesse S. Sayles, and Emilia P. Diaconescu. 2019. "An Integrative Climate Change Vulnerability Index for Arctic Aviation and Marine Transportation." *Nature Communications* 10 (1). https://doi.org/10.1038/s41467-019-10347-1

DMTI Lightbox. 2020. "CanMap GIS Data for GIS Mapping Software - DMTI Spatial." https://www.dmtispatial.com/canmap/

Doré, Guy, Fujun Niu, and Heather Brooks. 2016. "Adaptation Methods for Transportation Infrastructure Built on Degrading Permafrost." *Permafrost and Periglacial Processes* 27 (4): 352–364. https://doi.org/10.1002/PPP.1919

Dorough, Dalee S., Bridget Larocque, Kaviq Kaluraq, Daniel Taukie, David Sproule, and Whitney Lackenbauer. 2021. *Voices from the Arctic: Diverse Views on Canadian Arctic Security*. https://www.naadsn.ca/wp-content/uploads/2021/01/20-nov-ArcticVoicesProceedings-upload.pdf

ECCC (Environment and Climate Change Canada). 2020. *Climate Science 2050: Advancing Science and Knowledge on Climate Change*. Gatineau, QC. https://publications.gc.ca/collections/collection_2020/eccc/En4-414-2020-eng.pdf

Ellis, Michael J., Ivar Mendez, and Kelly Russell. 2020. "Preliminary Clinical Algorithm to Optimise Remote Delivery of Paediatric Concussion Care in Canada's North." *International Journal of Circumpolar Health* 79 (1). https://doi.org/10.1080/22423982.2020.1832390

Federation of Canadian Municipalities. 2018. "Guide: How to Develop an Asset Management Policy and Strategy." https://fcm.ca/en/resources/mamp/guidebook-how-develop-asset-management-policy-and-strategy

Firelight (The Firelight Group). 2022. *The Impacts of Permafrost Thaw on Northern Indigenous Communities. Firelight Research Inc.* Vancouver, BC. Prepared for the Canadian Climate Institute (formerly Canadian Institute for Climate Choices).

Ford, James D., D. Clark, T. Pearce, L. Berrang-Ford, L. Copland, J. Dawson, M. New, and S. L. Harper. 2019. "Changing Access to Ice, Land and Water in Arctic Communities." *Nature Climate Change* 9 (4): 335–339. https://doi.org/10.1038/s41558-019-0435-7

Ford, James D., Nicole Couture, Trevor Bell, and Dylan G. Clark. 2018. "Climate Change and Canada's North Coast: Research Trends, Progress, and Future Directions." *Environmental Reviews* 26 (1): 82–92. https://doi.org/10.1139/er-2017-0027

Ford, James D., Graham McDowell, and Tristan Pearce. 2015. "The Adaptation Challenge in the Arctic." *Nature Climate Change* 5: 1046–1053. https://doi.org/10.1038/nclimate2723

Fox, Shari, Esa Qillaq, Ilkoo Angutikjuak, Dennis Joseph Tigullaraq, Robert Kautuk, Henry Huntington, Glen E. Liston, and Kelly Elder. 2020. "Connecting Understandings of Weather and Climate: Steps towards Co-Production of Knowledge and Collaborative Environmental Management in Inuit Nunangat." *Arctic Science* 6 (3): 267–278. https://doi.org/10.1139/as-2019-0010

Funston, Bernard. 2014. *Emergency Preparedness in Canada's North: An Examination of Community Capacity*. http://www.mun.ca/harriscentre/Emergency_Preparedness.pdf

References

Gearheard, Shari, Claudio Aporta, Gary Aipellee, and Kyle O'Keefe. 2011. "The Igliniit Project: Inuit Hunters Document Life on the Trail to Map and Monitor Arctic Change." *Canadian Geographer* 55 (1): 42–55. https://doi.org/10.1111/j.1541-0064.2010.00344.x

George, Jane. 2006. "Climate Change Hits Roads and Airports in Nunavik." *Nunatsiaq News*, September 8. https://nunatsiaq.com/stories/article/climate_change_hits_roads_and_airports_in_nunavik/

Golder. 2021. *Guide on Climate Change Adaptation for the Mining Sector*. The Mining Association of Canada. https://mining.ca/resources/guides-manuals/guide-on-climate-change-adaptation-for-the-mining-sector/

Government of Canada. 2021. "Nutrition North Canada: Eligible Communities." https://www.nutritionnorthcanada.gc.ca/eng/1415540731169/1415540791407#tpc2

Government of Northwest Territories. 2020. *Capital Estimates 2021-2022*. https://www.fin.gov.nt.ca/sites/fin/files/resources/2021-22_capital_estimates.pdf

Government of Nunavut. 2014. *Nunavut Airports 20 Year Infrastructure Needs Assessment 2014 - 2034*. Iqaluit, NU. http://assembly.nu.ca/sites/default/files/TD%2096-4(3)%20EN%20Nunavut%20Airports%2020-year%20Infrastructure%20Needs%20Assessment%202014-2034.pdf

Hatcher, Scott V., and Donald L. Forbes. 2015. "Exposure to Coastal Hazards in a Rapidly Expanding Northern Urban Centre, Iqaluit, Nunavut." *Source: Arctic* 68 (4): 453–471. https://doi.org/10.14430/arctic4526

Hjort, Jan, Olli Karjalainen, Juha Aalto, Sebastian Westermann, Vladimir E Romanovsky, Frederick E Nelson, Bernd Etzelmüller, and Miska Luoto. 2018. "Degrading Permafrost Puts Arctic Infrastructure at Risk by Mid-Century." *Nature Communications* 9 (1). https://doi.org/10.1038/s41467-018-07557-4

Holzworth, Robert H., James B. Brundell, Michael P. McCarthy, Abram R. Jacobson, Craig J. Rodger, and Todd S. Anderson. 2021. "Lightning in the Arctic." *Geophysical Research Letters* 48 (7). https://doi.org/10.1029/2020GL091366

Hori, Yukari, William A. Gough, Benita Tam, and Leonard J.S. Tsuji. 2018. "Community Vulnerability to Changes in the Winter Road Viability and Longevity in the Western James Bay Region of Ontario's Far North." *Regional Environmental Change* 18 (6): 1753–1763. https://doi.org/10.1007/S10113-018-1310-1

Human Rights Watch. 2020. *"My Fear Is Losing Everything": The Climate Crisis and First Nations' Right to Food in Canada*. https://www.hrw.org/report/2020/10/21/my-fear-losing-everything/climate-crisis-and-first-nations-right-food-canada

Huntington, Henry P, Shari Gearheard, Lene Kielsen Holm, George Noongwook, Margaret Opie, and Joelie Sanguya. 2017. "Sea Ice Is Our Beautiful Garden: Indigenous Perspectives on Sea Ice in the Arctic." In *Sea Ice*, edited by David N. Thomas, 583–599. John Wiley & Sons. https://doi.org/10.1002/9781118778371.ch25

Huot, S., H. Ho, A. Ko, S. Lam, P. Tactay, J. MacLachlan, and R. K. Raanaas. 2019. "Identifying Barriers to Healthcare Delivery and Access in the Circumpolar North: Important Insights for Health Professionals." *International Journal of Circumpolar Health* 78 (1). https://doi.org/10.1080/22423982.2019.1571385

Infrastructure Canada. 2019. "Canada Helps Protect Inuvik Mike Zubko Airport from Impacts of Climate Change." Government of Canada. Ottawa, ON. https://www.canada.ca/en/office-infrastructure/news/2019/06/canada-helps-protect-inuvik-mike-zubko-airport-from-impacts-of-climate-change.html

IPCC (Intergovernmental Panel on Climate Change). 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by H-O Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, et al. Cambridge University Press. In Press. Cambridge.

ITK (Inuit Tapiriit Kanatami). 2018. *Inuit Statistical Profile 2018*. https://www.itk.ca/wp-content/uploads/2018/08/Inuit-Statistical-Profile.pdf

ITK (Inuit Tapiriit Kanatami). 2019. *Inuit Nunangat Housing Strategy*. https://www.itk.ca/inuit-nunangat-housing-strategy/

ITK (Inuit Tapiriit Kanatami). 2020. *Access to Drinking Water in Inuit Nunangat*. ITK Quarterly Research Briefing, Issue no. 2. https://www.itk.ca/wp-content/uploads/2020/12/ITK_Water_English_07.pdf

ITK (Inuit Tapiriit Kanatami). 2021. *The Digital Divide: Broadband Connectivity in Inuit Nunangat*. ITK Quarterly Research Briefing, Issue no. 3. https://www.itk.ca/wp-content/uploads/2021/08/ITK_Telecomms_English_08.pdf

Jong, Michael, Ivar Mendez, and Robert Jong. 2019. "Enhancing Access to Care in Northern Rural Communities via Telehealth." *International Journal of Circumpolar Health* 78 (2). https://doi.org/10.1080/22423982.2018.1554174

Karanasios, Konstantinos, and Paul Parker. 2017. "Recent Developments in Renewable Energy in Remote Aboriginal Communities, NWT, Canada." *Papers in Canadian Economic Development* 16: 41–53.

Kates, Robert W., William R. Travis, and Thomas J. Wilbanks. 2012. "Transformational Adaptation When Incremental Adaptations to Climate Change Are Insufficient." *Proceedings of the National Academy of Sciences of the United States of America* 109 (19): 7156–7161. https://doi.org/10.1073/PNAS.1115521109

Kilabuk, Elaine, Franco Momoli, Ranjeeta Mallick, Deborah Van Dyk, Christopher Pease, Alice Zwerling, Sharon Edmunds Potvin, and Gonzalo G. Alvarez. 2019. "Social Determinants of Health among Residential Areas with a High Tuberculosis Incidence in a Remote Inuit Community." *J Epidemiol Community Health* 73 (5): 401–406. https://doi.org/10.1136/JECH-2018-211261

Labbé, Jolène, James D. Ford, Malcolm Araos, and Melanie Flynn. 2017. "The Government-Led Climate Change Adaptation Landscape in Nunavut, Canada." *Environmental Reviews* 25 (1): 12–25. https://doi.org/10.1139/er-2016-0032

LaDuke, Winona, and Deborah Cowen. 2020. "Beyond Wiindigo Infrastructure." *South Atlantic Quarterly* 119 (2): 243–268. https://doi.org/10.1215/00382876-8177747

Lamoureux, Scott, Donald L Forbes, Trevor Bell, Gavin K Manson, A C A Rudy, J Lalonde, M Brown, I R Smith, T S James, and N J Couture. 2015. "The Impact of Climate Change on Infrastructure in the Western and Central Canadian Arctic." In *From Science to Policy in the Western and Central Canadian Arctic: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization*, edited by G.A. Stern and A Gaden, 301–341. ArcticNet. Quebec, QC.

Lasserre, Frédéric. 2022. "Canadian Arctic Marine Transportation Issues, Opportunities and Challenges." *The School of Public Policy Publications*. http://dx.doi.org/10.11575/sppp.v15i1.72626

Lochead, David. 2021. "Not Just Iqaluit: Clyde River Experiencing Water Problems." *Nunatsiaq News*, November 26. https://nunatsiaq.com/stories/article/not-just-iqaluit-clyde-river-experiencing-water-problems/

Lovekin, Dave, Barend Dronkers, and Ben Thibault. 2016. *Power Purchase Policies for Remote Indigenous Communities in Canada: Research on Government Policies to Support Renewable Energy Projects*. Pembina Institute. https://www.pembina.org/reports/power-purchase-policies-for-remote-indigenous-communities.pdf

Lovekin, Dave, and Dylan Heerema. 2019. "Diesel, Renewables, and the Future of Canada's Remote Communities." Pembina Institute. https://www.pembina.org/blog/remote-microgrids-intro

Maracle, Tobi Jeans, Glenna Tetlichi, Norma Kassi, and David Natcher. 2018. "Caribou and the Politics of Sharing." In *When the Caribou Do Not Come: Indigenous Knowledge and Adaptive Management in the Western Arctic*, edited by Brenda Parlee and Ken J Caine. UBC Press. Vancouver.

Masrur, Arif, Andrey N. Petrov, and John DeGroote. 2018. "Circumpolar Spatio-Temporal Patterns and Contributing Climatic Factors of Wildfire Activity in the Arctic Tundra from 2001–2015." *Environmental Research Letters* 13 (1): 014019. https://doi.org/10.1088/1748-9326/aa9a76

Melvin, April M., Peter Larsen, Brent Boehlert, James E. Neumann, Paul Chinowsky, Xavier Espinet, Jeremy Martinich, et al. 2016. "Climate Change Damages to Alaska Public Infrastructure and the Economics of Proactive Adaptation." *Proceedings of the National Academy of Sciences* 114 (2): E122–E131. https://doi.org/10.1073/pnas.1611056113

Microsoft. 2019. "Microsoft Releases 12 Million Canadian Building Footprints as Open Data." Microsoft Bing Blogs [Media release], March 13. https://blogs.bing.com/maps/2019-03/microsoft-releases-12-million-canadian-building-footprints-as-open-data

Morse, Kathryn. 2003. *The Nature of Gold: An Environmental History of the Klondike Gold Rush*. University of Washington Press. https://doi.org/10.2307/25443112

Mortensen, Lucia, Anne Merrild Hansen, and Alexander Shestakov. 2017. "How Three Key Factors Are Driving and Challenging Implementation of Renewable Energy Systems in Remote Arctic Communities." *Polar Geography* 40 (3): 163–185. https://doi.org/10.1080/1088937X.2017.1329758

Murray, Nick. 2021. "Iqaluit's Water Crisis Has Cost the City $1.5 Million so Far." *CBC News*, November 4. https://www.cbc.ca/news/canada/north/iqaluit-water-crisis-costs-city-1.6237366

NAEDB (National Aboriginal Economic Development Board). 2016. *Recommendations on Northern Infrastructure to Support Economic Development*. http://www.naedb-cndea.com/reports/recommendations-on-northern-infrastructure.pdf

Naylor, Angus W., James D. Ford, Tristan Pearce, David Fawcett, Dylan Clark, and James van Alstine. 2021. "Monitoring the Dynamic Vulnerability of an Arctic Subsistence Food System to Climate Change: The Case of Ulukhaktok, NT." *PLoS ONE* 16 (9 September). https://doi.org/10.1371/journal.pone.0258048

Ness, Ryan, Dylan G. Clark, Julien Bourque, Dena Coffman, and Dale Beugin. 2021. *Under Water: The Costs of Climate Change for Canada's Infrastructure*. Canadian Climate Institute (formerly Canadian Institute for Climate Choices). https://climatechoices.ca/wp-content/uploads/2021/09/Infrastructure-English-FINAL-jan17-2022.pdf

Neufeld, Hannah T., and Chantelle A. M. Richmond. 2017. "Impacts of Place and Social Spaces on Traditional Food Systems in South-western Ontario." *International Journal of Indigenous Health* 12 (1): 93–115. https://doi.org/10.18357/ijih112201716903

NRCan (Natural Resource Canada). n.d. "Minerals Sector Employment." https://www.nrcan.gc.ca/science-data/science-research/earth-sciences/earth-sciences-resources/earth-sciences-federal-programs/minerals-sector-employment/16739#s2

NTI (Nunavut Tunngavik Ink). 2020. *Nunavut's Infrastructure Gap*. Iqaluit, NU. https://www.tunngavik.com/files/2020/10/2020.10.20-Nunavuts_Infrastructure_Gap_Report_vf.pdf

Nutrition North. 2020. "Cost of the Revised Northern Food Basket in 2019-2020." https://www.nutritionnorthcanada.gc.ca/eng/1610462030814/1610462073967

Obu, Jaroslav, Sebastian Westermann, Andreas Kääb, and Annett Bartsch. 2018. "Ground Temperature Map, 2000-2016, Northern Hemisphere Permafrost." *Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA*. https://doi.org/10.1594/PANGAEA.888600

Office of the Auditor General of Canada. 2017. *Civil Aviation Infrastructure in the North*. Government of Canada. Ottawa, ON.

O'Neill, H. Brendan, Stephen A. Wolfe, and Caroline Duchesne. 2020. Ground Ice Map of Canada. Geological Survey of Canada, Open File 8713, (version 1). Natural Resources Canada. https://doi.org/10.4095/326885

Patterson, M., S. Flinn, and K. Barker. 2018. "Addressing Tuberculosis among Inuit in Canada." *Canada Communicable Disease Report* 44 (3/4): 82–85. https://doi.org/10.14745/CCDR.V44I34A02

PCIC (Pacific Climate Impacts Consortium). 2019. "Statistically Downscaled Climate Scenarios." University of Victoria. Victoria, B.C. https://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios

Qikiqtani Inuit Association. 2014. *Qikiqtani Truth Commission: Community Histories 1950-1975*. Inhabit Media Incorporated. Iqaluit, NU.

Radosavljevic, Boris, Hugues Lantuit, Wayne Pollard, Paul Overduin, Nicole Couture, Torsten Sachs, Veit Helm, and Michael Fritz. 2016. "Erosion and Flooding—Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada." *Estuaries and Coasts* 39 (4): 900–915.

Ready, Elspeth, and Peter Collings. 2020. "'All the Problems in the Community Are Multifaceted and Related to Each Other': Inuit Concerns in an Era of Climate Change." *American Journal of Human Biology* n/a (n/a): e23516. https://doi.org/10.1002/ajhb.23516

Resilient Analytics. 2021. "What Is IPSS?" https://resilient-analytics.com/ipss

Ritchie, Haley. 2021. "Na-Cho Nyak Dun Farm Wins Arctic Inspiration Prize." *Yukon News*, February 27. https://www.yukon-news.com/news/na-cho-nyak-dun-farm-wins-arctic-inspiration-prize/

Samson, Rachel. 2021. "Cost-Benefit Analysis Is the Wrong Tool for Tackling Climate Change." *Policy Options*, November 1. https://policyoptions.irpp.org/magazines/november-2021/cost-benefit-analysis-is-the-wrong-tool-for-tackling-climate-change/

Sheppard, Lola, Mason White, Alex Bodkin, and Sarah Gunawan. 2017. "Eldercare Centre." Lateral Office. http://lateraloffice.com/NU-ELDERCARE-CENTRE-2016-17

Simonee, Natasha, Jayko Alooloo, Natalie Ann Carter, Gita Ljubicic, and Jackie Dawson. 2021. "Sila Qanuippa? (How's the Weather?): Integrating Inuit Qaujimajatuqangit and Environmental Forecasting Products to Support Travel Safety around Pond Inlet, Nunavut in a Changing Climate." *Weather, Climate, and Society*, August. https://doi.org/10.1175/WCAS-D-20-0174.1

Smit, Barry, Ian Burton, Richard J.T. Klein, and J. Wandel. 2000. "An Anatomy of Adaptation to Climate Change and Variability." *Climatic Change* 45 (1): 223–251. https://doi.org/10.1023/A:1005661622966

Smith, Mike W., and Daniel W. Riseborough. 2002. "Climate and the Limits of Permafrost: A Zonal Analysis." *Permafrost and Periglacial Processes* 13 (1): 1–15. https://doi.org/10.1002/PPP.410

Sohns, Antonia, James D. Ford, Mylene Riva, Brian Robinson, and Jan Adamowski. 2019. "Water Vulnerability in Arctic Households." *Arctic* 72 (3): 300–316. https://doi.org/10.14430/arctic68884

Standards Council of Canada. 2020. "Northern Infrastructure Standardization Initiative: Building a Climate-Resilient Future with Northern Standards." https://www.scc.ca/en/nisi

Statistics Canada. 2016. "Index of Remoteness." Government of Canada. https://www150.statcan.gc.ca/n1/en/catalogue/17260001

Statistics Canada. 2017. "2016 Census. Statistics Canada Catalogue No. 98-316-X2016001." *2016 Census*. Ottawa.

Statistics Canada. 2019. "Table 23-10-0264-01 Detailed Provincial and Territorial Transportation Expenditures, by Mode of Transportation, Transport Canada (x 1,000,000)." Government of Canada. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2310026401

Statistics Canada. 2021a. "Table 36-10-0402-01 Gross Domestic Product (GDP) at Basic Prices, by Industry, Provinces and Territories." Government of Canada. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610040201

Statistics Canada. 2021b. " Table 17-10-0005-01 Population Estimates on July 1st, by Age and Sex." https://www150.statcan.gc.ca/t1/

tbl1/en/tv.action?pid=1710000501

Streicker, John. 2016. *Yukon Climate Change Indicators and Key Findings 2015*. Northern Climate Exchange, Yukon Research Center, Yukon College. https://www.yukonu.ca/sites/default/files/inline-files/Indicator_Report_Final_web.pdf

Transport Canada. 2021. "Airports Capital Assistance Program." Government of Canada. https://tc.canada.ca/en/programs/airports-capital-assistance-program

Transport Canada. 2022a. "List of Airports Owned by Transport Canada." Government of Canada. https://tc.canada.ca/en/aviation/operating-airports-aerodromes/list-airports-owned-transport-canada

Transport Canada. 2022b. "List of Ports Owned by Transport Canada." https://tc.canada.ca/en/marine-transportation/ports-harbours-anchorages/list-ports-owned-transport-canada

Truth and Reconciliation Commission of Canada. 2015a. *Canada's Residential Schools: The Inuit and Northern Experience: The Final Report of the Truth and Reconciliation Commission of Canada*. Truth and Reconciliation Commission of Canada.

Truth and Reconciliation Commission of Canada. 2015b. *Truth and Reconciliation Commission of Canada: Calls to Action*. https://www2.gov.bc.ca/assets/gov/british-columbians-our-governments/indigenous-people/aboriginal-peoples-documents/calls_to_action_english2.pdf

Underwood, Fox, and Stefania Bertazzon. 2020. "The Impacts of Climate Change on Health and Development in Canadian Arctic and Sub-Arctic Communities in the Twenty-First Century: A Systematic Review." In *Extreme Weather Events and Human Health*, edited by Rais Akhtar, 27–40. Springer. Cham. https://doi.org/10.1007/978-3-030-23773-8_3

Uzarowski, Ludomir, Mark Musial, and Rabiah Rizvi. 2018. "Challenge of Permafrost Degradation Impact on Airport and Road Pavements." In *Transportation Association of Canada Conference - Innovation and Technology: Evolving Transportation, TAC 2018*.

Vachon, J, V Gallant, and W Siu. 2018. "Tuberculosis in Canada, 2016." *Canada Communicable Disease Report* 44 (3/4): 75–81. https://doi.org/10.14745/CCDR.V44I34A01

Vogt, Nina. 2021. "Influence of Permafrost Characteristics on Vegetation Change in Yukon and Northwest Territories, Canada." Master's thesis. University of Alberta. https://doi.org/10.7939/r3-pjcm-aj83

Wallace, Kenyon. 2019. "Beyond Frozen." *The Star*, July 4. https://projects.thestar.com/climate-change-canada/nunavut/

Wenzel, George. 2009. "Canadian Inuit Subsistence and Ecological Instability—If the Climate Changes, Must the Inuit?" *Polar Research* 28 (1): 89–99. https://doi.org/10.1111/j.1751-8369.2009.00098.x

White, Mason, Ceara Allen, Nikole Couchard, and Joseph Yau. 2010. "Health Hangars." Lateral Office. Toronto, ON. http://lateraloffice.com/HEALTH-HANGARS-2010

Young, T. Kue, Susan Chatwood, and Gregory P. Marchildon. 2016. "Healthcare in Canada's North: Are We Getting Value for Money?" *Healthcare Policy* 12 (1): 59–70.

Yukon Bureau of Statistics. 2020. *Yukon Employment Historical Data 2011 — 2020*. Whitehorse, YT. https://yukon.ca/en/yukon-employment-historical-data-2011-2020

Zhao, Yijie, and Laxmi Sushama. 2020. "Aircraft Takeoff Performance in a Changing Climate for Canadian Airports." *Atmosphere* 11 (4): 418. https://doi.org/10.3390/atmos11040418

MORE PUBLICATIONS FROM THE CLIMATE INSTITUTE:

TIP OF THE ICEBERG:
Navigating the known and unknown costs of climate change for Canada

UNDER WATER:
The costs of climate change for Canada's infrastructure

THE HEALTH COSTS OF CLIMATE CHANGE:
How Canada can adapt, prepare, and save lives

CANADA’S NET ZERO FUTURE:
Finding our way in the global transition

MARKING THE WAY:
How legislating climate milestones clarifies pathways to long-term goals

11 WAYS TO MEASURE CLEAN GROWTH:
Unlocking prosperity through progress on climate change, economic and social goals

climateinstitute.ca